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Acknowledgment: This research was supported by the Advanced Research Projects Agency, Nuclear Monitoring Research Office, under Project VELA-UNIFORM, and accomplished under the technical direction of the Air Force Technical Applications Center under Contract No. F33657-70-C-0311.

STATISTICAL DISCRIMINATION

Quarterly Report No. 2

1 December 1969 to 31 March 1970

Stanley J. Laster, Program Manager
Area Code 214, 238-6521

TEXAS INSTRUMENTS INCORPORATED
Services Group
P.O. Box 5621
Dallas, Texas 75222

Contract No. F 33657-70-C-0311
Amount of Contract: \$222,240
Beginning 25 August 1969
Ending 14 September 1970

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Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D. C. 20333

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office
ARPA Order No. 624
AFTAC Project No. VELA/T/0702/E/ASD

15 April 1970

services group

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TEXAS INSTRUMENTS

INCORPORATED

13500 NORTH CENTRAL EXPRESSWAY • DALLAS, TEXAS

SERVICES GROUP

15 April 1970

Air Force Technical Applications Center
VELA Seismological Center
Headquarters, USAF
Washington, D.C. 20333

Attention: Lt. John Woods

Subject: 2nd Quarterly Report Covering Period 1 December 1969
to 31 March 1970

Identification: AFTAC Project VELA T/0702/B/ASD
Statistical Discrimination
ARPA Order 624
ARPA Program Code 9F10
Contractor: Texas Instruments Incorporated
Contract: F33657-70-C-0311
Effective Date: 25 August 1969
Amount: \$222,250
Expiration Date: 14 September 1970
Project Manager: Stanley J. Laster

Gentlemen:

The following is the second quarterly report of statistical-discrimination work performed under Contract F33657-70-C-0311. The work performed and plans are described by task, with more details being provided in the attachment.

I. INTRODUCTION

Research under the current contract consists of the following tasks:

- (1) Continuing use of the Seismic-Event Classification Software Package (SECSP) at the Seismic-Array Analysis Center in Washington
- (2) A literature search to determine the observed differences between the seismic signatures of nuclear and chemical explosions

- (3) Comparison of the discrimination capabilities of the Alaskan Long-Period Array (ALPA) and the Large-Aperture Seismic Array (LASA) in Montana, using recordings of the same events when possible and comparing results with those published for the Norwegian Seismic Array (NORSAR)
- (4) Processing of previously recorded events from LASA to determine the optimum procedure for using LASA for event discrimination and study of various techniques for improving long-period discriminants

II. WORK SUMMARY AND PLANS BY TASKS

- (1) TI is continuing to build additional ensembles for various geographical areas and types of events (e.g., the Kurile Islands, deep events, Novaya Zemlya explosions). The efficiency of various combinations of short-period discriminants is being tested, and use of combined long- and short-period discriminants is just beginning. A group of 29 new short-period events obtained from SAAC (three of them also having long-period data) should provide a good test of the various "learning patterns."

The contract monitor has provided a list of 30 events to be run through SECSP. All of these appear to be available on library tape at SAAC, but only six have been run through the event processor. A request has been made to have the other events processed, so the running of SECSP on these events will be delayed until this has been done.

- (2) The literature search comparing chemical and nuclear explosions is proceeding slowly. The primary interest is in differences observable at teleseismic distances; there have been very few such observances of chemical events. The final results of this study will be reported later in a special report, so this topic is not covered in the attachment to this report.
- (3) Programs have been written to measure high-resolution spectral peaks in short time gates of a long-period signal; this allows group-velocity measurements for each peak. The higher frequency peaks are presumably associated with higher-order surface modes. Hopefully, such energy will be useful for discrimination purposes. Theoretical seismograms generated under a previous contract will be used to test further the method of isolating higher-mode energy.

- (4) The matched-filtering study is almost complete, and chirp filters of appropriate length have been found to work almost as well as master events for some continental areas. In addition, simple measurements of group velocity give a reasonable prediction of how effective matched filtering is for a given event.

Long-period spectra for the various events are being computed for use in the design of discriminants. The chief need now is for more long-period data.

Action by AFTAC

None

Financial Status

Financial status will be presented in the next AMSR to be submitted in the latter part of April.

Very truly yours,

Stanley J. Laster

Stanley J. Laster, Program Manager
Texas Instruments Incorporated

SJL:ms
Attachment

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CLASSIFICATION

REPORT OF PROGRESS AGAINST SELECTED MILESTONES (See instructions on reverse before filling in)				ARPA ORDER NUMBER 624	
2. PROJECT AFTAC Project No. VELA T/0702			3. COMPONENT SEISMIC DISCRIMINATION TECHNIQUES		
4. NAME AND LOCATION OF PREPARING ACTIVITY Texas Instruments Incorporated Services Group Dallas, Texas 75222				5. CONTRACT NUMBER F33657-70-C-0311	
				6. REPORT FOR MONTH ENDING 31 March 1970	
Code a	Milestone b	Scheduled Completion Date c	Estimated Completion Date d	Date Completed e	Remarks f
A-1	Checkout SECSF programs; send to Washington; successfully process one event	1 Dec 69		15 Jan 70	
A-2	Determine discriminants to use in SECSF; submit recommendation to AFTAC for approval	15 Dec 69	1 May 70		
A-3	Specify offline processing needed to use LP discriminants in SECSF for data recorded at LASA	15 Nov 69	15 May 70		
A-4	Determine modifications necessary and statistics to use in applying SECSF to ALPA events	1 Jan 70	1 May 70		No ALPA data available
A-5	Complete processing of Eurasian seismic events (recorded at LASA and ALPA) using SECSF	1 Sep 70	1 Sep 70		
A-6	Prepare special report summarizing results of SECSF processing	15 Sep 70	15 Sep 70		
B-1	Conduct literature search and publish report on differences between seismic signatures of nuclear and chemical explosions	1 May 70	1 Jun 70		
C-1	Obtain data ensembles with continental paths recorded at LASA and ALPA	15 Feb 70	1 Jun 70		No ALPA data available

TYPED NAME AND TITLE Stan Laster, Program Manager		SIGNATURE		TELEPHONE 214- 238-2997	DATE SIGNED 15 April 70
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SD FORM 350
1 JAN 66

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CLASSIFICATION

REPORT OF PROGRESS AGAINST SELECTED MILESTONES <small>(See instructions on reverse before filling in)</small>				1. ARPA ORDER NUMBER 624	
2. PROJECT AF TAC Project No. VELA T/0702		3. COMPONENT SEISMIC DISCRIMINATION TECHNIQUES			
4. NAME AND LOCATION OF PREPARING ACTIVITY Texas Instruments Incorporated Services Group Dallas, Texas 75222				5. CONTRACT NUMBER F33657-70-C-0311	
				6. REPORT FOR MONTH ENDING 31 March 1970	
Code a	Milestone b	Scheduled Completion Date c	Estimated Completion Date d	Date Completed e	Remarks f
C-2	Prepare special report comparing various methods of detecting and isolating higher-mode surface waves and usefulness of such waves for discrimination	15 May 70	1 Jun 70		
C-3	Investigate effectiveness of various methods for designing matched filters used in detecting long-period Rayleigh-wave energy	15 Jan 70	15 Mar 70		
C-4	Specify methods to use, if any, to remove noise before computing long-period discriminants	15 Dec 69	15 May 70		
C-5	Prepare special report discussing effects of noise on various discrimination statistics	1 Aug 70	1 Aug 70		
C-6	Specify statistics to use in evaluating combined discrimination capability of LASA and ALPA	1 Jun 70	1 Jul 70		No ALPA data available
C-7	Complete processing of previously recorded LASA and ALPA events	1 Sep 70	1 Sep 70		
C-8	Prepare special report summarizing combined LASA-ALPA discrimination capabilities	15 Sep 70	15 Sep 70		
C-9	Prepare final report summarizing all research performed under contract	15 Sep 70	15 Sep 70		

TYPED NAME AND TITLE Stan Laster, Program Manager		SIGNATURE		TELEPHONE 214- 238-2997	DATE SIGNED 15 April 70
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SD FORM 350
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ATTACHMENT

A. SECSPP PROCESSING

The Seismic-Event Classification Software Package (SECSPP) is a set of programs used in classifying an unknown seismic event as either an earthquake or an explosion. Its ultimate purpose is to detect clandestine underground nuclear explosions.

The package consists of two phases — learning and classification. The learning phase uses statistics from an ensemble of known earthquakes and explosions (a "learning pattern"). Currently, the package uses statistics from short-period traces only, but long-period statistics will also be used in the near future.

The learning phase develops transformation matrices and vectors that will accomplish certain objectives. Four independent pattern-recognition methods are now in use:

- Class clustering, which clusters events of like class
- Class separation, which separates events of unlike class
- Likelihood ratio test, which estimates the probability that the given event belongs in class 1 or 2. (A simplified version, linear discriminant, assumes the same covariance matrix for each class and makes a decision based on the distance from the two class means.)
- Adaptive algorithm, designed to produce a vector whose dot product with the event statistics is negative for one class and positive for the other



The statistics now being used are P30 mean square, autocorrelation mean square, envelope difference, and spectral ratio. Bodywave magnitude, dominant period, and signal-to-noise (S/N) ratio are statistics to be tried in the future. Plans also call for testing new learning patterns by using various combinations of the statistics. The various statistics have been studied by means of 2-dimensional plots. The P30 mean square and envelope difference (both measures of complexity) have been shown to be strongly correlated -- as are bodywave magnitude and spectral ratio. Surprisingly (because of the similarity in method of computation), the P30 mean square and autocorrelation mean square show little correlation. In addition, autocorrelation mean square is less effective than P30 mean square as a discriminant, so the former will probably be dropped.

The initial phases of the processing with the SECSP programs used a learning ensemble of 16 earthquakes and 10 explosions assembled under a previous identification contract. This learning ensemble was too small to give an accurate statistical representation of earthquakes and explosions and did not represent a good geographical distribution for the area of interest. All except one of the explosions were from a single area, while the majority of the earthquakes were from the Kurile-Kamchatka area. In such a situation, discrimination could arise from geographic differences rather than from actual differences between explosions and earthquakes. Thus, a new and larger ensemble of earthquakes and explosions was assembled that hopefully would be more representative of the area under study.

The new ensemble comprises 42 earthquakes and 40 explosions selected from three other in-house ensembles in addition to the original one. Due to the limited number of test sites, all but four of the explosions are again from the same area.

The earthquakes were selected for geographical location; they were scattered over Russia, China, and bordering countries, and there are five



from Northern Africa. Northern Russia, which has very few earthquakes, is the only area not represented. All of the earthquakes have depths of < 70 km. This learning ensemble will be used by subsequent SECSP runs, although 16 new earthquakes and 13 new explosions which have just been obtained will be added as soon as feasible.

We also have an ensemble of 35 earthquakes deeper than 90 km. Due to the limited number of in-house deep earthquakes, all deep events have been taken, regardless of location; this gives a worldwide distribution of deep earthquakes. Deep-earthquake traces resemble explosion traces in many respects and, therefore, are harder to distinguish from explosions. Working with the deep quakes will be a good test of the classification program and should reveal subtle differences among the three event classes.

Power spectra are computed for the ensemble of shallow-focus events (depth < 70 km) recorded at LASA. The ensemble includes 39 and 42 earthquakes. The average spectrum for each of the two classes of events is computed and shown in Figure 1a. The spectra are normalized to the total power in the 0.85- to 2.80-Hz band before averaging inasmuch as the bodywave magnitude m_b ranges from 3.9 to 6.4 for the explosions and from 4.1 to 6.1 for the earthquakes. A comparison of the average spectra is indicative of the effectiveness of the spectral-ratio discriminant for distinguishing between earthquakes and nuclear explosions; e.g., the average nuclear explosion generates relatively more energy in the 1-3 cps band and relatively less in the .5-1 cps band than does the average earthquake.

Average noise spectra computed from a time gate preceding the signal for the two classes of events are shown in Figure 1b. The spectra agree closely below 1.4 Hz — but above, the earthquake-ensemble noise is approximately 2 db higher than the explosion-ensemble noise, a result which would tend to degrade the spectral-ratio discriminant for low-magnitude explosions.

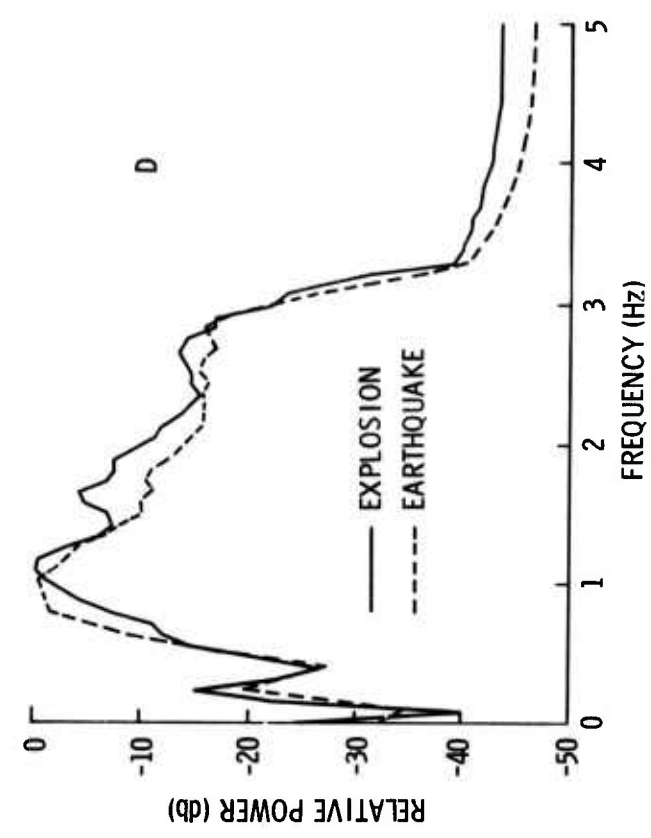
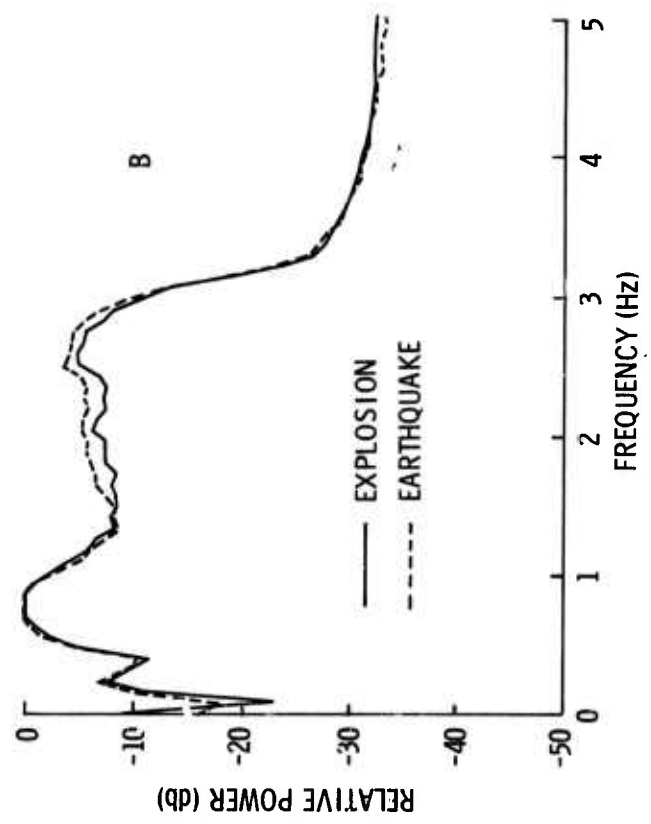
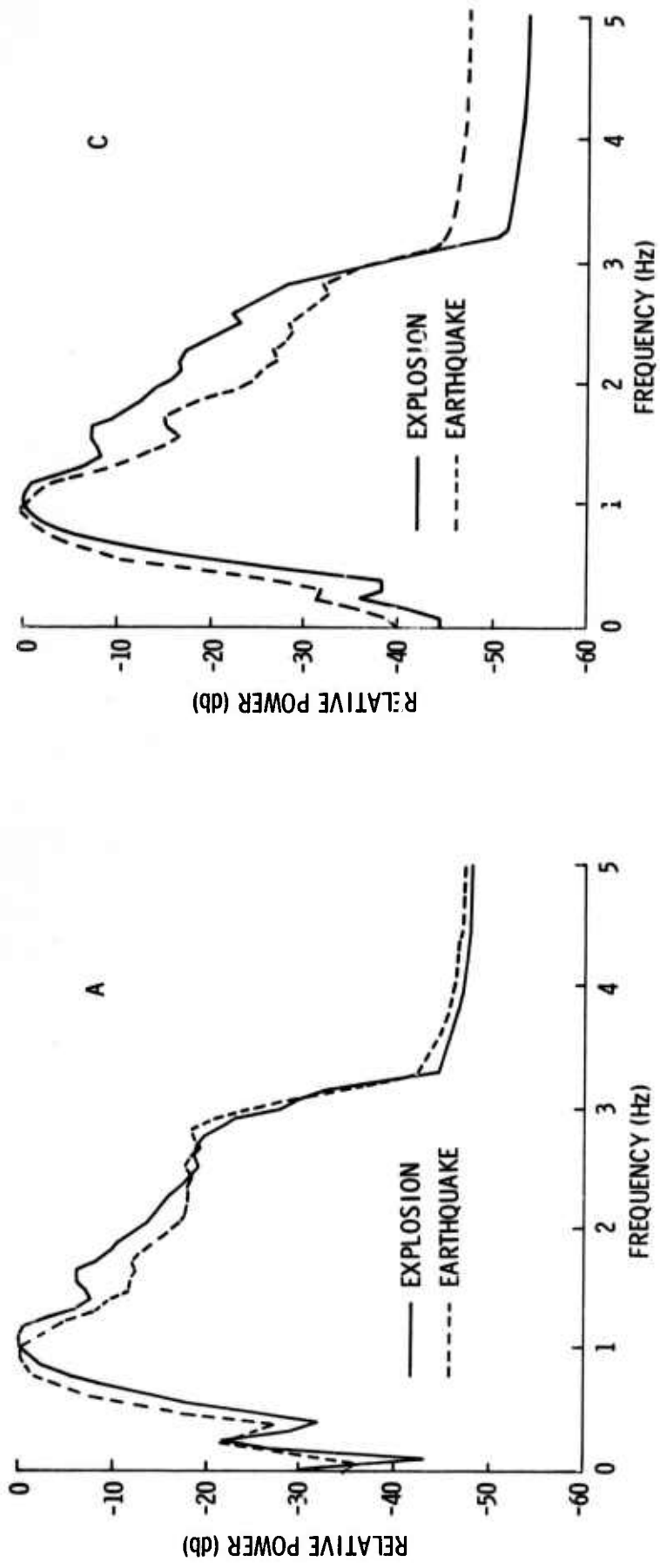


Figure 1. Various Power-Spectra Plots for Ensemble of 39 Explosions and 42 Earthquakes Having Shallow Focus





Next, the events in each class are separated by magnitude ($m_b < 5.0$ and $m_b > 5.0$) and average spectra computed, giving the results shown in Figures 1c and 1d. For this ensemble of events, the effectiveness of the spectral-ratio discriminant is largely reduced by the low S/N ratio for events with $m_b < 5.0$.

B. CONTINENTAL-PATH STUDIES — DETECTION OF HIGHER-ORDER SURFACE-WAVE MODES

Preparation of the necessary computer programs has received the main effort in the task to detect and separate any Rayleigh and higher-order shear-mode energy from long-period LASA beams. These programs compute and plot the theoretical dispersion curves from layered models, the traveltimes for the various wave modes, and the maximum entropy power spectra of the time-partitioned seismograms.

The theoretical dispersion curve for the LASA are computed for four models: Fort Peck, TI1, ^{*} the University of Wisconsin Model 3 (UW3), and the USGS Model 3 (USGS3). Dispersion curves for these models are similar, with only slight differences between them in the 0.0- to 0.1-Hz spectral region. Figures 2, 3, 4, and 5 show the dispersion curves for the Fort Peck, TI1, UW3, and USGS3 models. From the dispersion curves, theoretical arrival times are computed for the Rayleigh mode and the first higher-mode shear waves given some epicentral distance. While it is not realistic to assume that the LASA model applies over the entire great circle route, it provides a starting point for the search for higher-order modes. The LASA model which appears to give the best results in preliminary analysis will be used.

^{*}Texas Instruments Incorporated, 1967: Continuation of Basic Research in Crustal Studies, Final Report, Contract AF 49(638)-1588, AFOSR, 15 July.

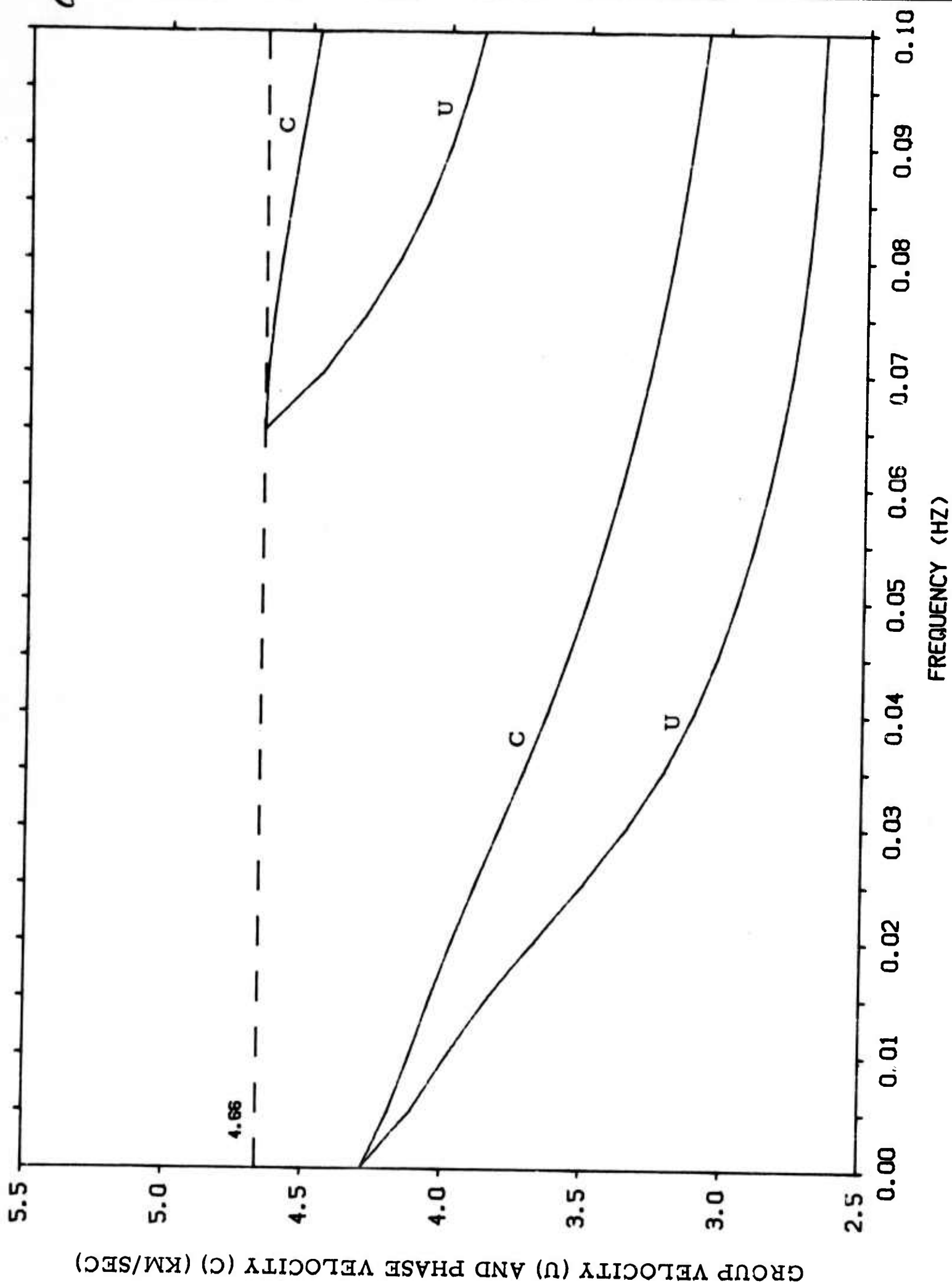


Figure 2. Theoretical Dispersion Curves for Fort Peck LASA Long-Period Model

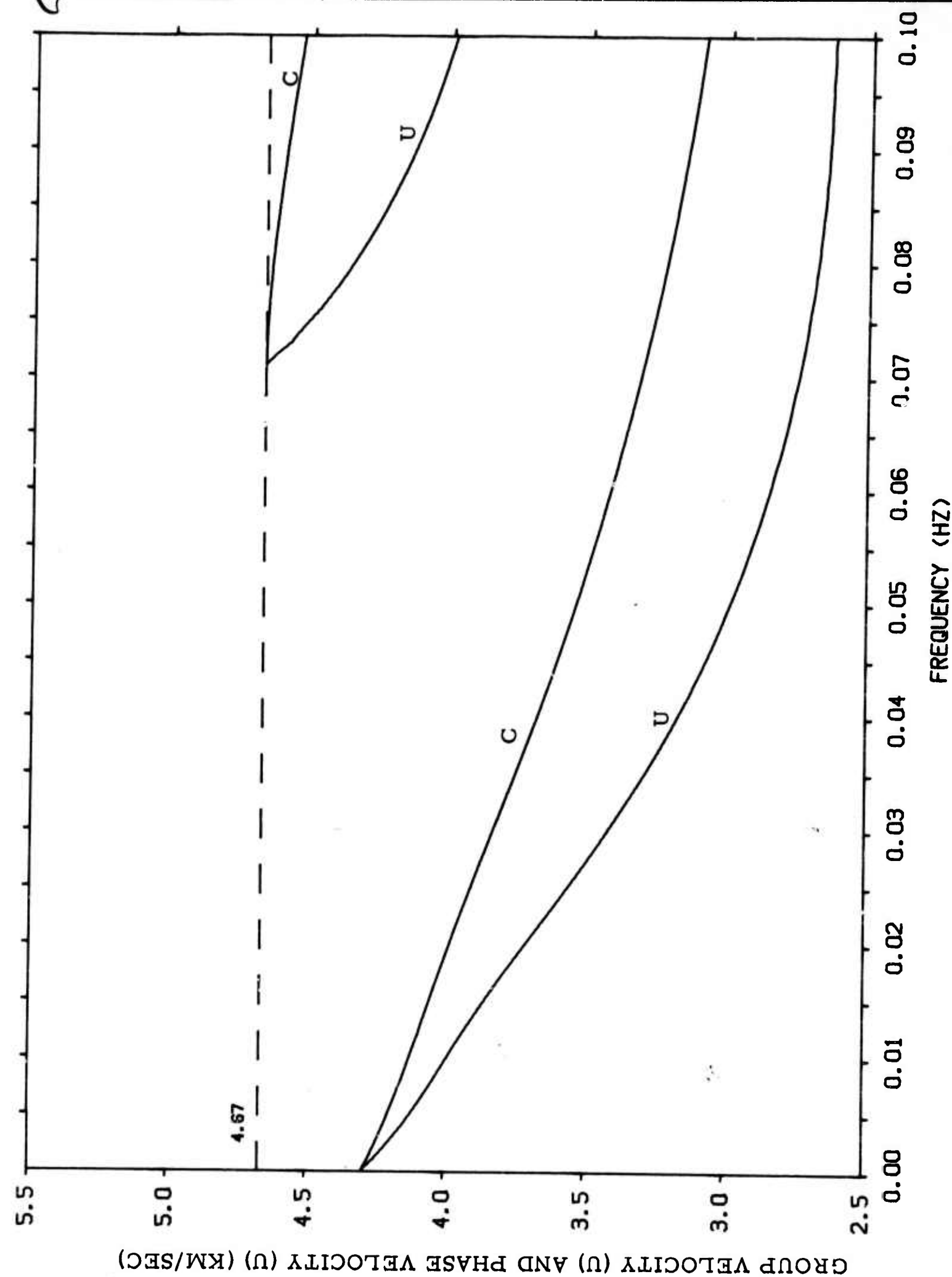


Figure 3. Theoretical Dispersion Curves for TII LASA Long-Period Model

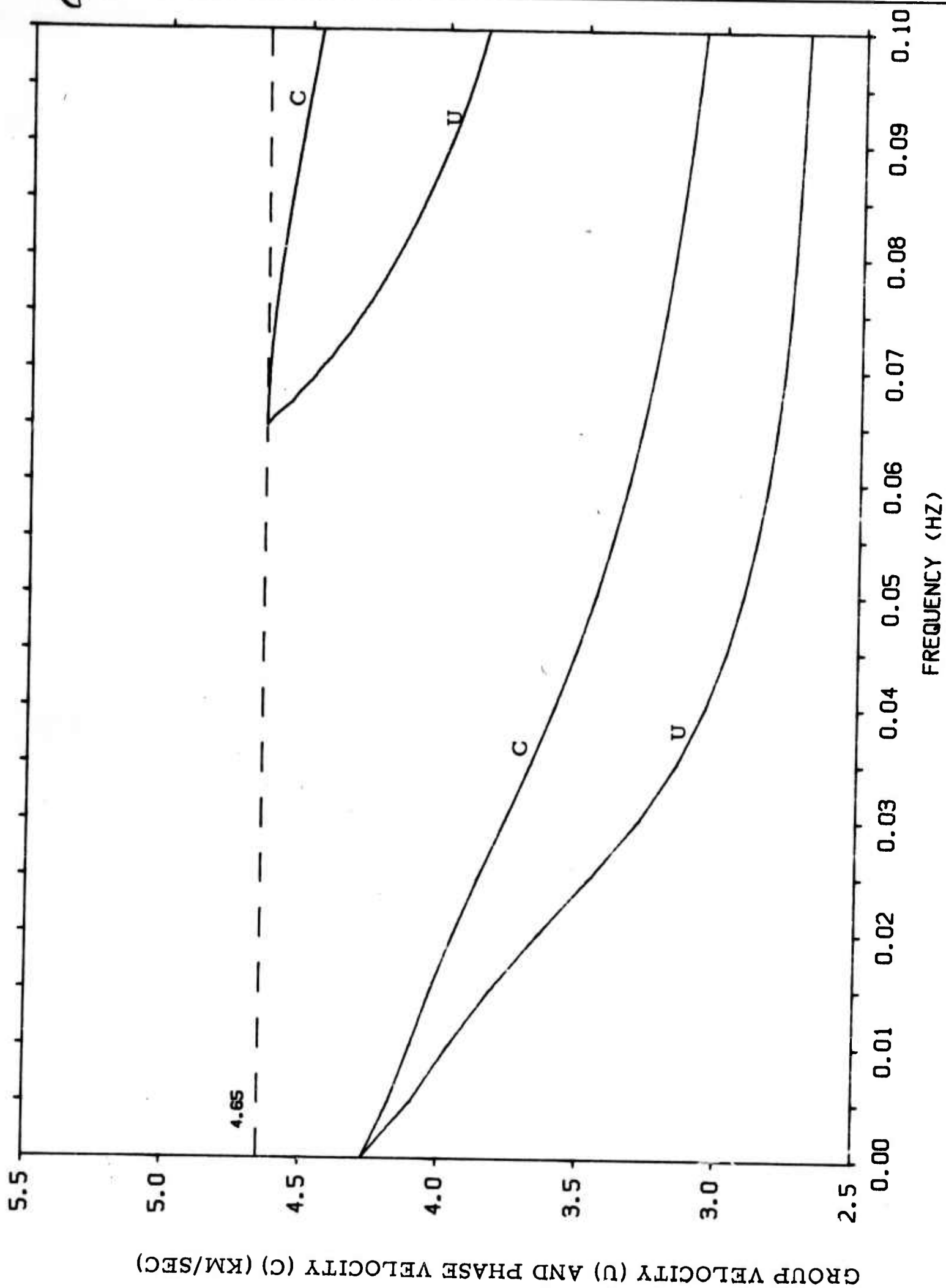


Figure 4. Theoretical Dispersion Curves for UW3 LASA Long-Period Model

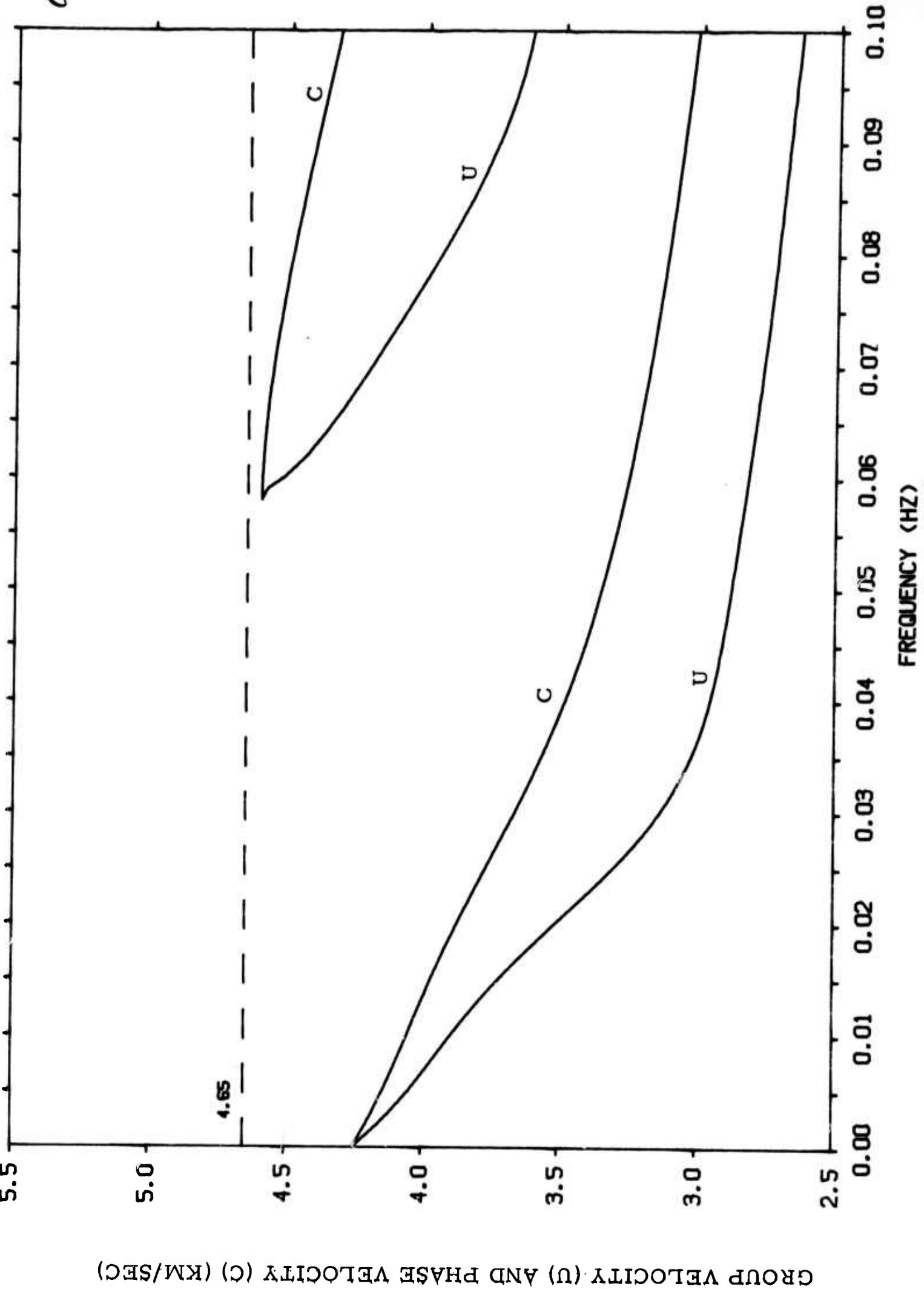


Figure 5. Theoretical Dispersion Curves for USGS3 LASA Long-Period Model





Two events have been examined for higher-mode content.

Event L-37, a teleseismic explosion ($m_b = 6.1$) has a signal-power-to-noise-power ratio of approximately 25 db. Event L-01, an earthquake ($m_b = 4.5$) in the Greenland Sea with an epicentral distance of approximately 5761 km, has an excellent signal-power-to-noise-power ratio of about 100 db. The vertical component of the long-period seismograms is partitioned into blocks containing 100 or 200 time points (100 or 200 sec of real time). The first block was taken approximately 300 sec before the expected first arrival. Each successive block of points overlaps the preceding block by half its length to give some redundancy to the computed power spectra. The maximum-entropy power spectrum is then computed for each block of points using prediction-error filter lengths of 50 for 200-point blocks and 25 for 100-point blocks. The frequency and power of all spectral peaks are tabulated and assigned an arrival time equal to the middle of the partition.

Figure 6 shows results of event L-37 for which the T11 model is used. The spectral peaks picked from the power spectra are plotted as circles filled by an amount denoting the power relative to the largest peak. The most powerful peaks tend to cluster near the line of expected arrival. Such good agreement is unexpected because of the assumptions made in computing the arrival time. Inasmuch as L-37 is a subsurface explosion, little or no second-order shear-mode energy should be present. What appears to be possible second-order energy above 0.05 Hz and between 1900- and 2700-sec traveltimes may not be significant inasmuch as the power levels are consistent with the ambient noise. The three points around 0.04 Hz after 3300-sec traveltimes are definitely above ambient noise. Their identification must await further analysis.

The results for event L-01 are shown in Figure 7. The T11 model is used for the traveltime curve. For this event, the most powerful waves tend to arrive earlier than expected - by approximately 50 sec. Above 0.05 Hz, the difference increases to approximately 100 sec. This early arrival indicates that the surface layers through Eastern Canada have a higher propagation velocity than do the LASA models.

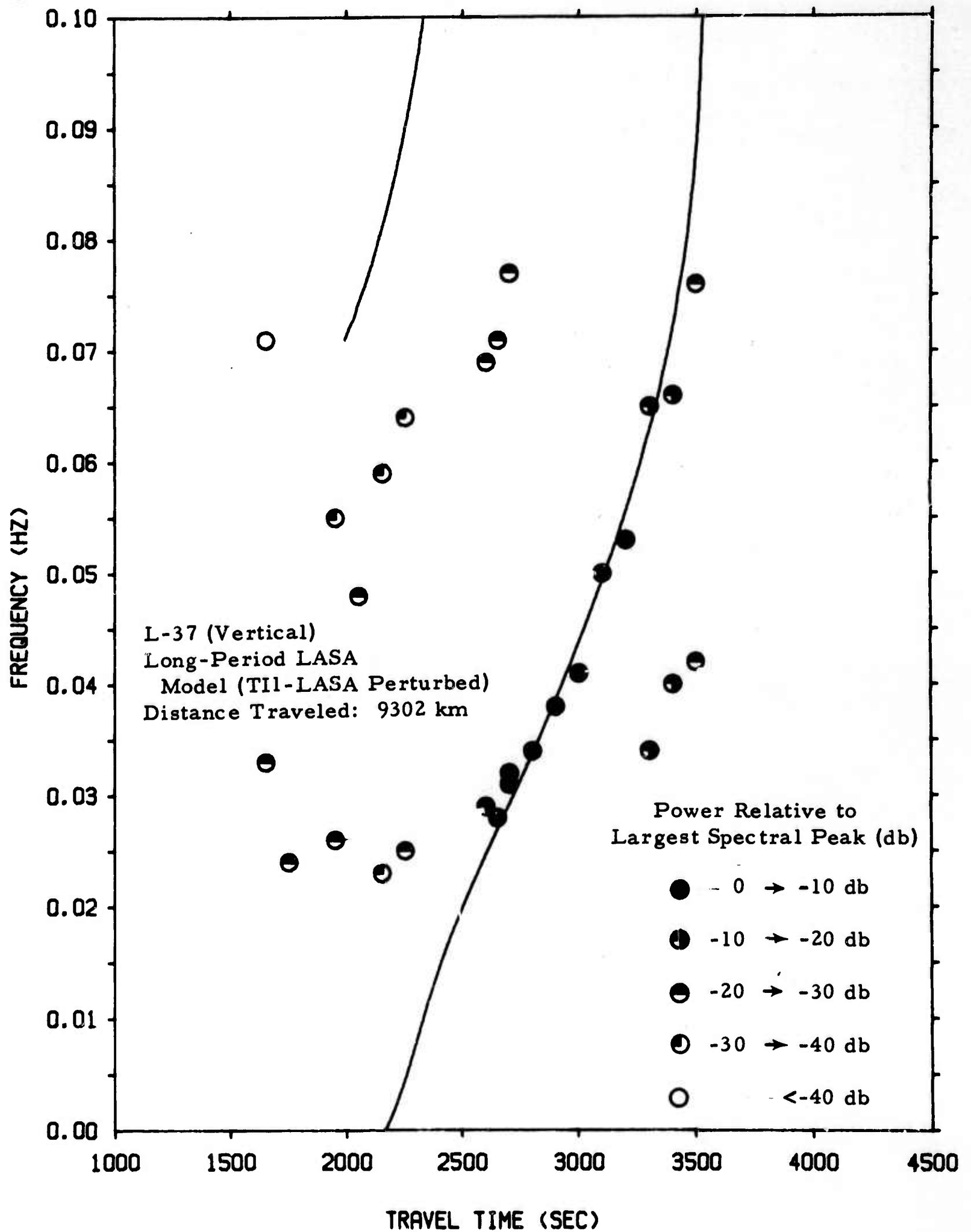


Figure 6. Event L-37 Power Spectra Showing Spectral Peaks

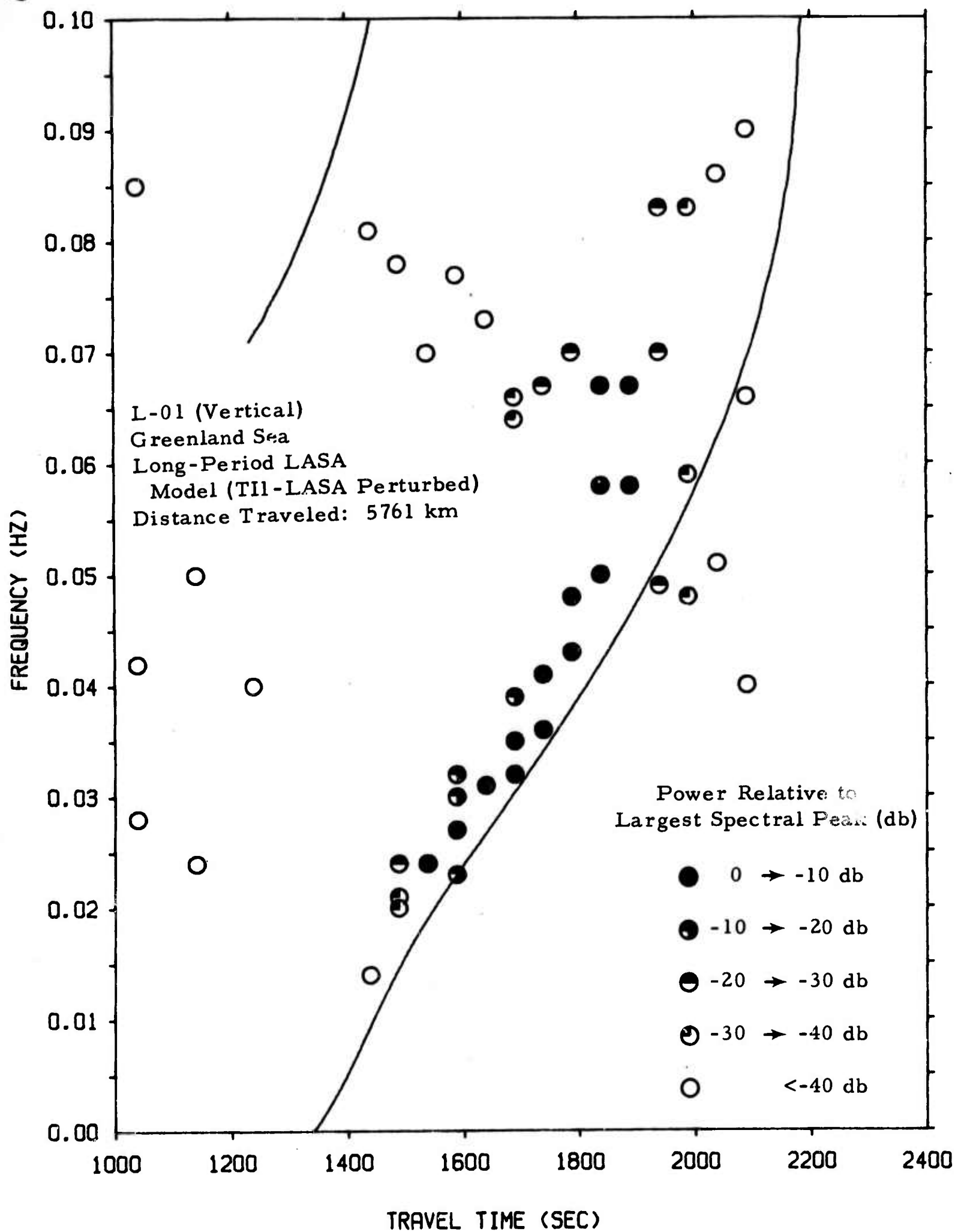


Figure 7. Event L-01 Power Spectra Showing Spectral Peaks



The cluster of points between 0.06 and 0.08 Hz arriving between 1300 and 1700 sec are possibly higher-mode energy. Having energy levels about 50 db less than the fundamental mode but still 40 to 50 db larger than the ambient noise level, these points may be artifacts generated by the analysis technique or perhaps arrivals of leaky modes not normally seen but visible here because of the large S/N ratio of this event. Both possibilities are being investigated. Theoretical seismograms of known content and dispersion generated under an earlier contract will be tested in the same way as the events to see if these peaks are real or anomalous.

C. LASA PROCESSING

1. Group-Velocity Analysis

Long-period surface waves from a group of explosions and earthquakes from the LASA seismometer arrays in Montana were analyzed, but only vertical and inline components were used because the transverse component was very erratic. Surface waves disperse when traveling in the earth because the phase velocity of propagation of surface waves depends on wave frequency; the original impulse spreads or disperses, with lower frequencies coming in before higher frequencies in the frequency band of interest.

A single analysis of the surface waves was programmed. The program, operating on the portion of the trace beginning approximately at the predicted Rayleigh-wave onset, uses an average of 800 points of data which are optionally bandpass-filtered in the time domain. The program then picks every peak and every trough in the filtered trace and assigns it an order number or sequence number. At each point, frequency and group velocity are computed. The group velocity is the wavelet's average velocity as it travels from source to receiver. Frequency is computed by numerically differentiating the order number with respect to arrival time. Finally, group velocity vs frequency is plotted for each point. The study used 26 teleseismic earthquakes and 11 teleseismic explosions from the present contract ensemble. All explosions are from a single area; the earthquakes are scattered over the globe.



Analysis results vary. The explosions, which generally have small surface waves, show the expected high degree of scatter and only slight trends in the plotted points. This result is due largely to the poor S/N ratio typical of explosions. Figure 8 is the best result obtained for an explosion. Its magnitude is 5.7. In addition, earthquakes with low S/N ratios also show a high degree of scatter, indicating that the lower the S/N ratio, the poorer the results. Figure 9 is an example of an earthquake with low S/N ratio.

From the geographical standpoint, the plots reveal that events from certain regions are much better than others. Events originating in the Southwest Pacific show very good results, with only slight scatter (Figure 10[†]). Better-than-average results are also found for events in Panama and South America (Figure 11) and in the Greenland Sea (Figure 12). At the opposite extreme are events from the Kurile Islands area (Figure 13); events from these islands and from neighboring Hokkaido and Kamchatka produce plots with a high scattering of points. The crust in the source region is complicated, and the path of surface waves from this area must pass through the complicated crust structure of the Aleutian Islands in reaching the LASA array; this is theorized as the reason for the poor results.

The scatter of the group-velocity curves should indicate roughly how much chirp-filtering the trace will enhance the peak signal. In general, the less scatter in the curve, the greater the signal enhancement so, on this basis, we predicted that chirp-filtering a Kurile Islands events would enhance the signal very little; workers on another contract found this to be the case.* The group-velocity curves should also help predict the average crust and the average dispersion curve over the path of the surface waves.

* Texas Instruments Incorporated, 1970: Seismic Array Processing Techniques, Quarterly Report No. 2, Contract F33657-70-C-0100, AFTAC, 3 March.

† Theoretical curve for oceanic path taken from R. Piermattei and A. Nowroozi, 1969, Dispersion of Rayleigh waves for purely oceanic paths in the Pacific: Bull., Seismological Society of America, v. 59, p. 1913, Fig. 9, Oct.

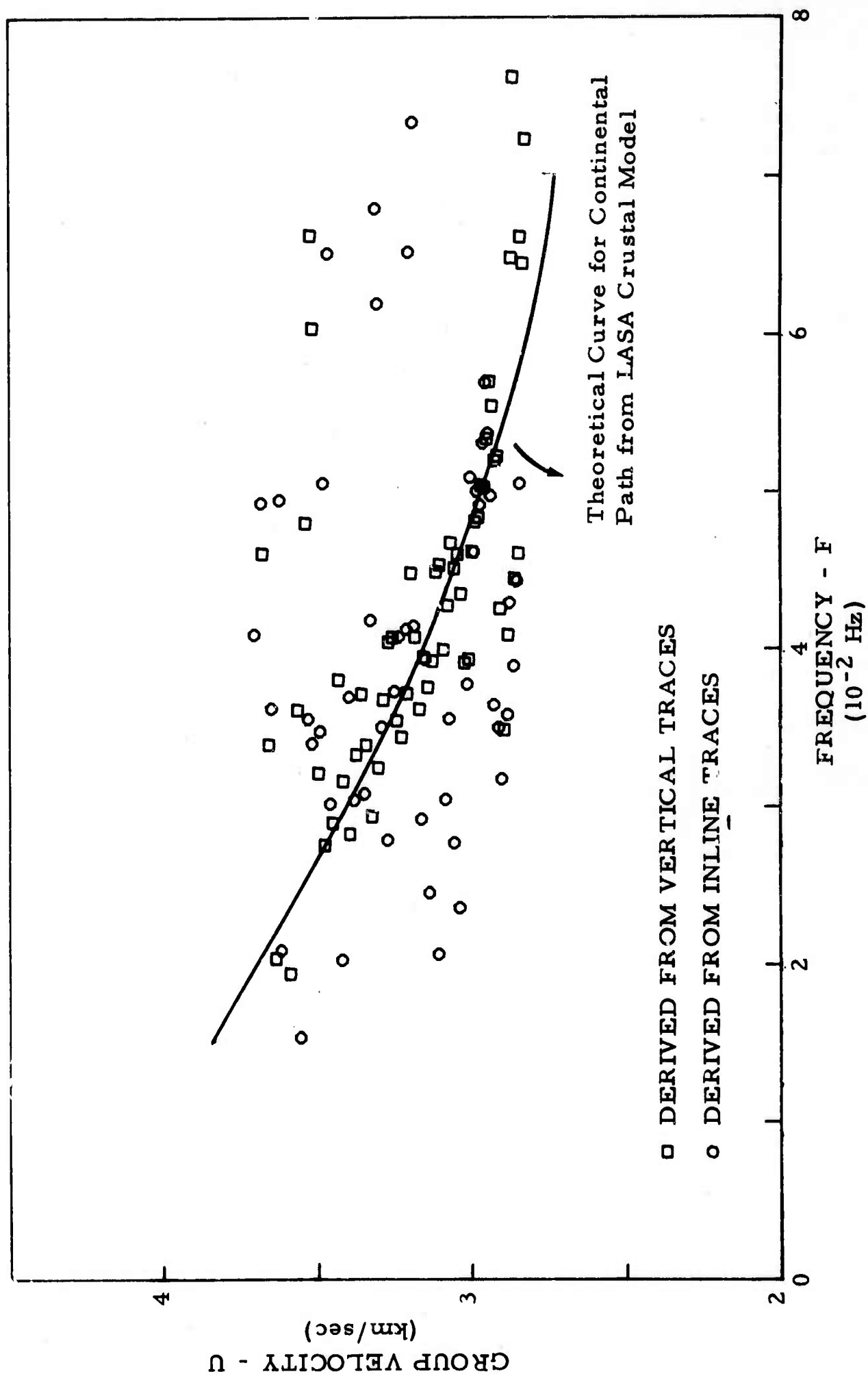


Figure 8. Group Velocity Vs Frequency for a teleseismic Nuclear explosion as Derived from Vertical and Inline Traces

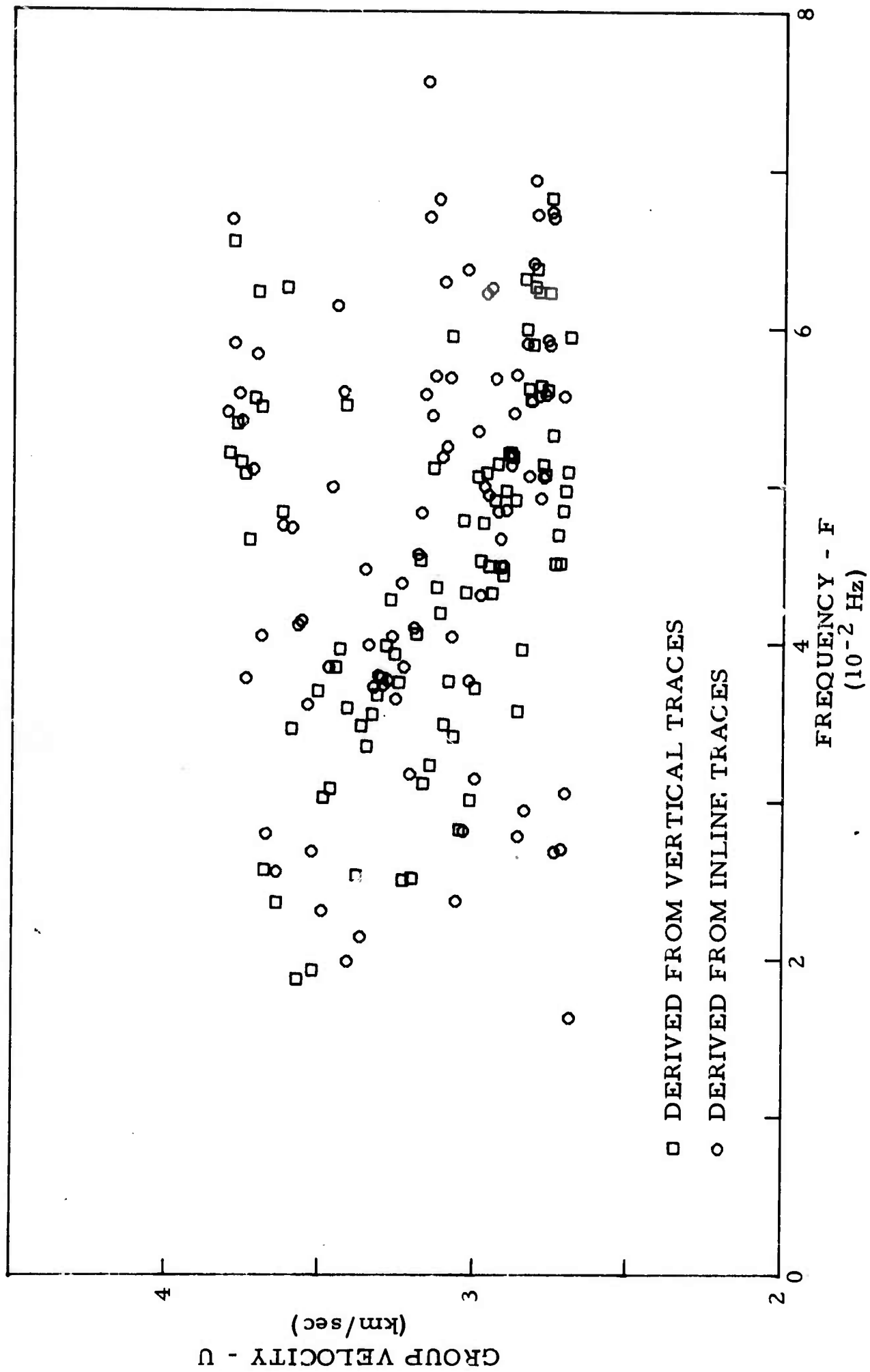


Figure 9. Group Velocity Vs Frequency for Earthquake in Eastern China as Derived from Vertical and Inline Traces

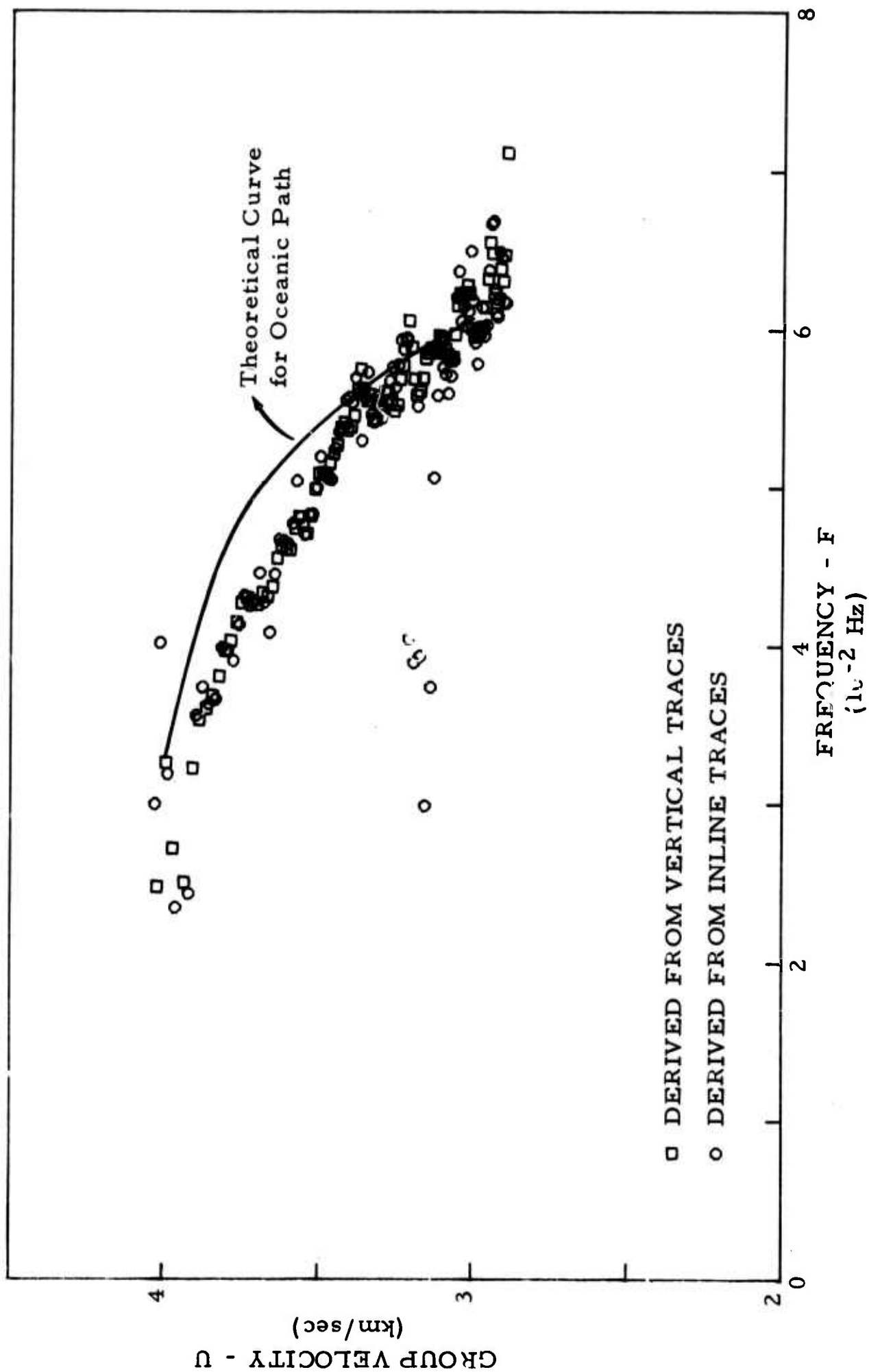


Figure 10. Group Velocity Vs Frequency for Earthquake in South Pacific as Derived from Vertical and Inline Traces

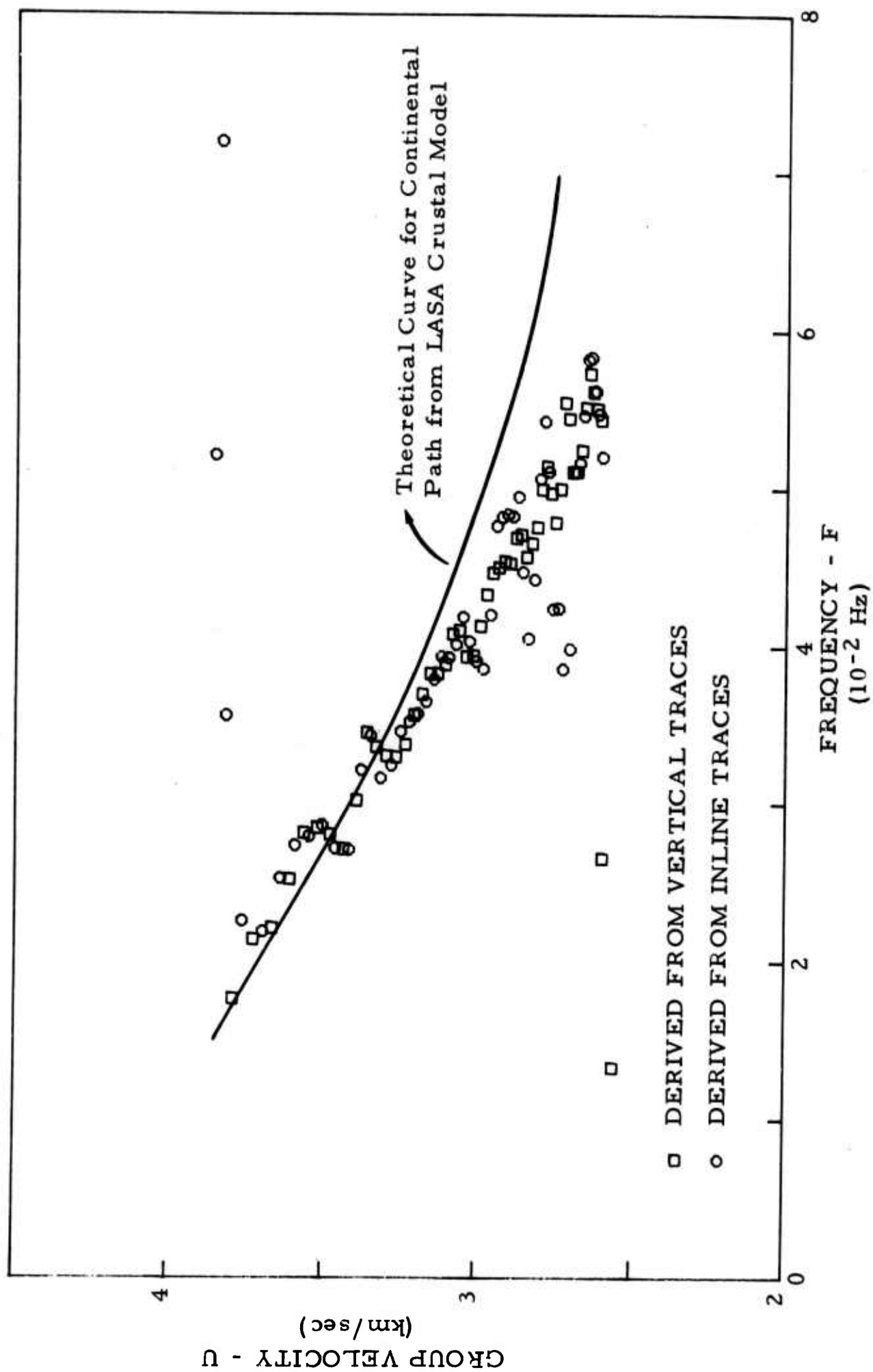


Figure 11. Group Velocity Vs Frequency for Earthquake in Panama as Derived from Vertical and Inline Traces

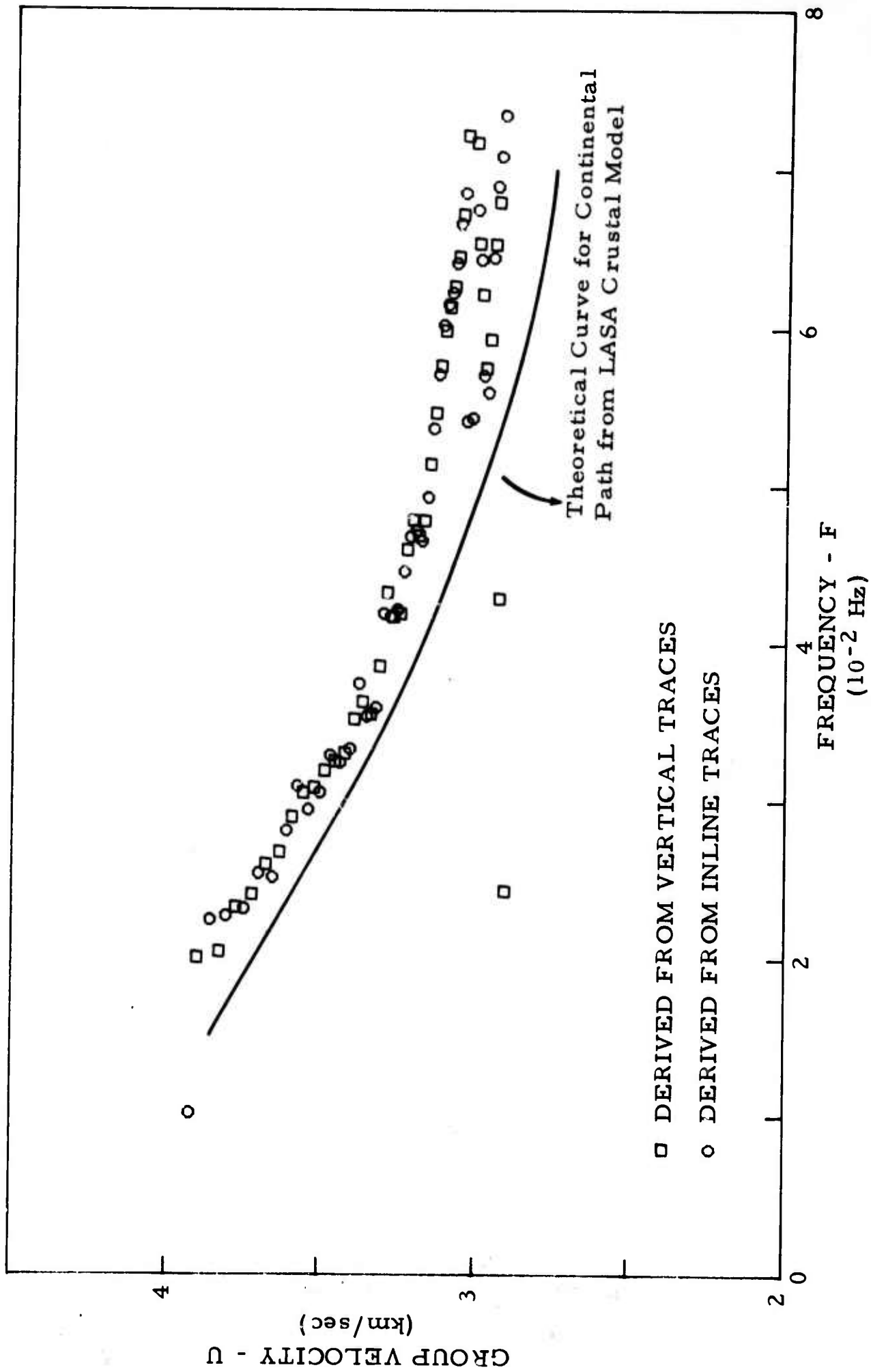


Figure 12. Group Velocity Vs Frequency for Earthquake in Greenland Sea as Derived from Vertical and Inline Traces

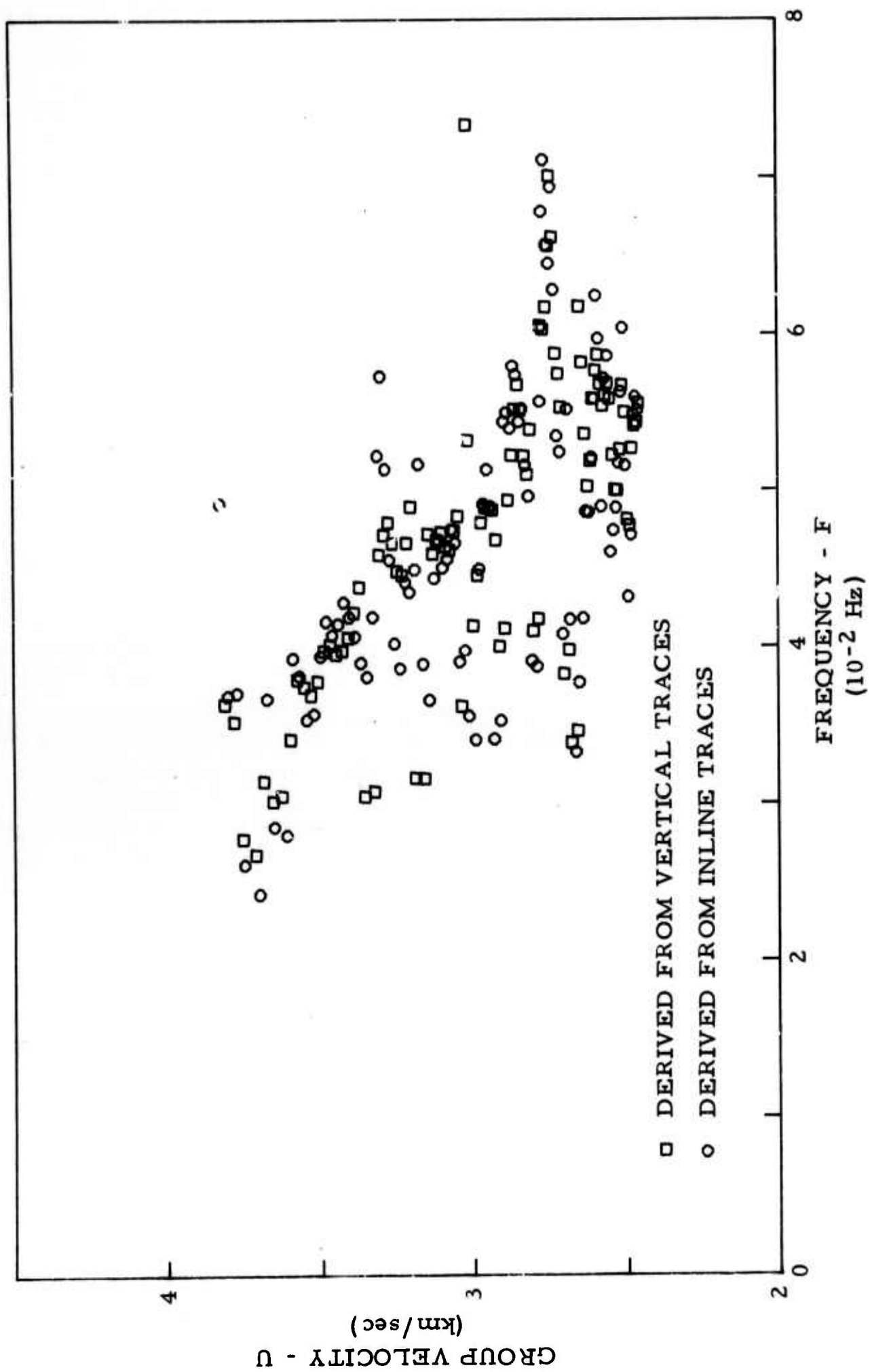


Figure 13. Group Velocity V_s Frequency for Earthquake in Kurile Islands as Derived from Vertical and Inline Traces



2. Matched Filtering

Application of the M_s vs m_b discriminant to shallow teleseismic events requires a good estimate of the long-period Rayleigh wave. Generally speaking, the LASA outputs beamsteered at Rayleigh velocity show significant waveform degradation due to poor S/N ratio at approximately $m_b < 4.5$ for earthquakes and $m_b < 5.7$ for explosions.

To examine certain data-processing techniques for enhancing S/N ratio, a program to matched-filter long-period Rayleigh waves has been written. Matched filtering is performed by crosscorrelating a matching waveform (filter) with the recorded time trace, the output for a perfect match between the filter and the noise-free time trace being the autocorrelation function of the filter.

Two types of matched filters have been applied to an ensemble of explosions ($4.8 \leq m_b \leq 6.1$) recorded at LASA. The first is a master-event (ME) filter. An event with good S/N ratio is chosen and the dispersed Rayleigh waveform partitioned from the time trace for use as the matched filter. The program truncates the filter at the nearest zero crossing and applies an 8-point cosine taper to each end; in addition, a zero-phase band-pass filter may be designed and convolved with the ME filter before matched filtering. This filter is then applied to other events with low S/N ratio occurring in the same area. The second type, a chirp filter, is generated by specifying the initial frequency f_0 , final frequency f_1 , and time duration L , where

$$R(t) = \begin{cases} \sin \left[2\pi \left(f_0 + \frac{f_1 - f_0}{2L} t \right) t \right] & 0 \leq t \leq L \\ 0, & \text{otherwise} \end{cases}$$

Both techniques have been previously used with varying success by many investigators.



Figure 14 plots the beamsteered vertical and inline traces for the events used. The sample rate of the data is 1 sec, and all plots presented in this section are scaled by setting the maximum trace deflection to 1 in.

The vertical Rayleigh-wave component of event L-37 ($m_b = 6.1$) is selected for the ME filter (Figure 15) because it exhibits the highest S/N ratio for events in the ensemble. The length is 800 sec, and a zero-phase high-cut filter at 0.1 Hz is applied to the ME filter. The ME filter is first applied to the entire time trace from which it is taken (L-37 vertical), giving the result shown in Figure 15. The output represents the best S/N ratio improvement to be expected from the ensemble of events. The S/N ratio is defined here as the maximum zero-to-peak amplitude of the signal divided by the rms of the noise preceding the signal. The ME filter is also applied to the inline horizontal trace (Figure 15). Ideally this output would exhibit a 90° phase shift relative to the vertical trace output. An S/N ratio improvement of approximately 2 over the input trace is indicated. The beamsteered horizontal traces at LASA generally show a much lower S/N ratio than do the corresponding vertical traces. Results of applying the ME filter to the remaining events (both vertical and inline traces) in the ensemble are presented in Figure 15; the events are ordered by decreasing bodywave magnitude. The time at which the peak in the matched-filter output is expected to occur is marked for each event. A peak in the outputs of the matched-filter vertical traces is obtained for events down to $m_b = 5.4$ except for event L-33.

Next, several chirp filters have been designed and applied to event L-37 to determine the best match. The process is one of trial and error in which initial and final frequencies are held at 0.025 Hz and 0.050 Hz, respectively, and the time duration of the filter is varied. The first filter, which is 800 sec long, results in the output shown in Figure 16; in this case, the chirp-filter frequency is changing too slowly, shifting the high frequencies early relative to the predicted peak. Next, a 600-sec chirp filter is applied;

L-30
 $M_b=5.3$

INLINE



VERTICAL



L-31
 $M_b=5.3$

INLINE



VERTICAL



L-34
 $M_b=4.9$

INLINE



VERTICAL



L-39
 $M_b=4.8$

INLINE



VERTICAL

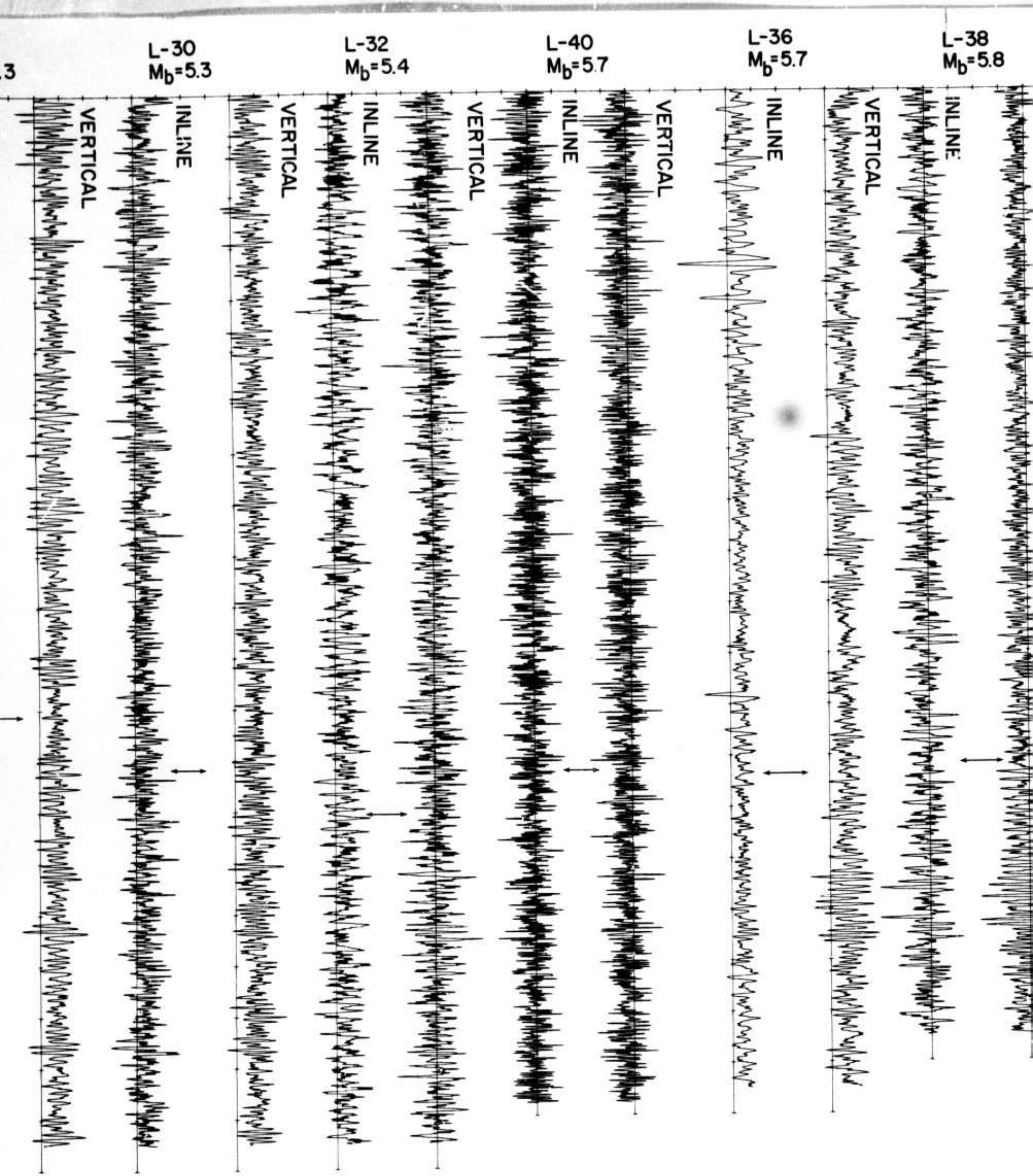


L-41
 $M=4.7$

INLINE



A.



Fig

B.

6
5.7

L-38
 $M_b = 5.8$

L-33
 $M_b = 5.9$

L-35
 $M_b = 6.1$

L-37
 $M_b = 6.1$

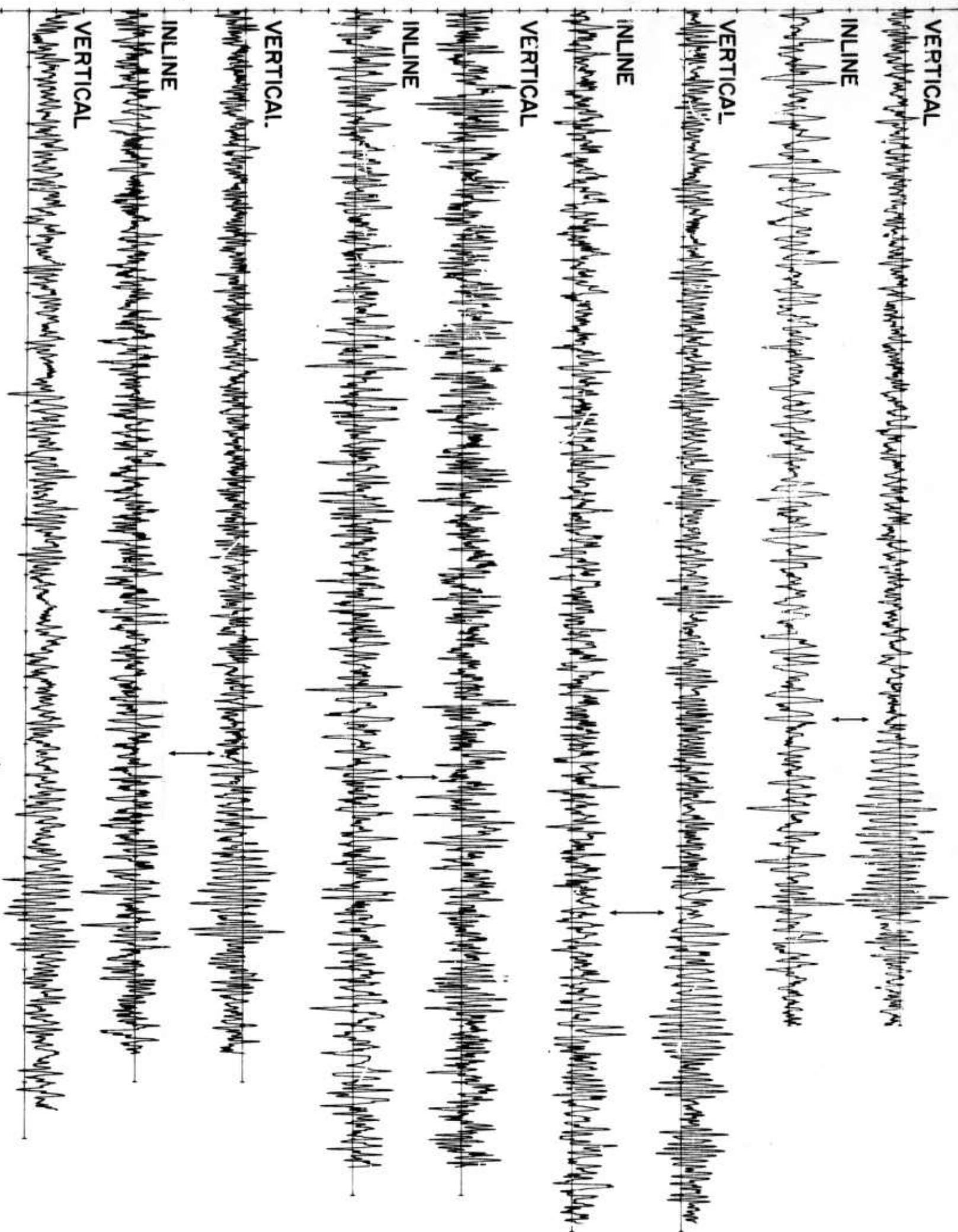


Figure 14. Plots of Beamsteered Vertical and Inline Traces for Ensemble of Explosions

9

L-30
 $M_b=5.3$

INLINE

VERTICAL

L-31
 $M_b=5.3$

INLINE

VERTICAL

L-34
 $M_b=4.9$

INLINE

VERTICAL

L-39
 $M_b=4.8$

INLINE

VERTICAL

L-41
 $M_b=4.7$

INLINE

A.

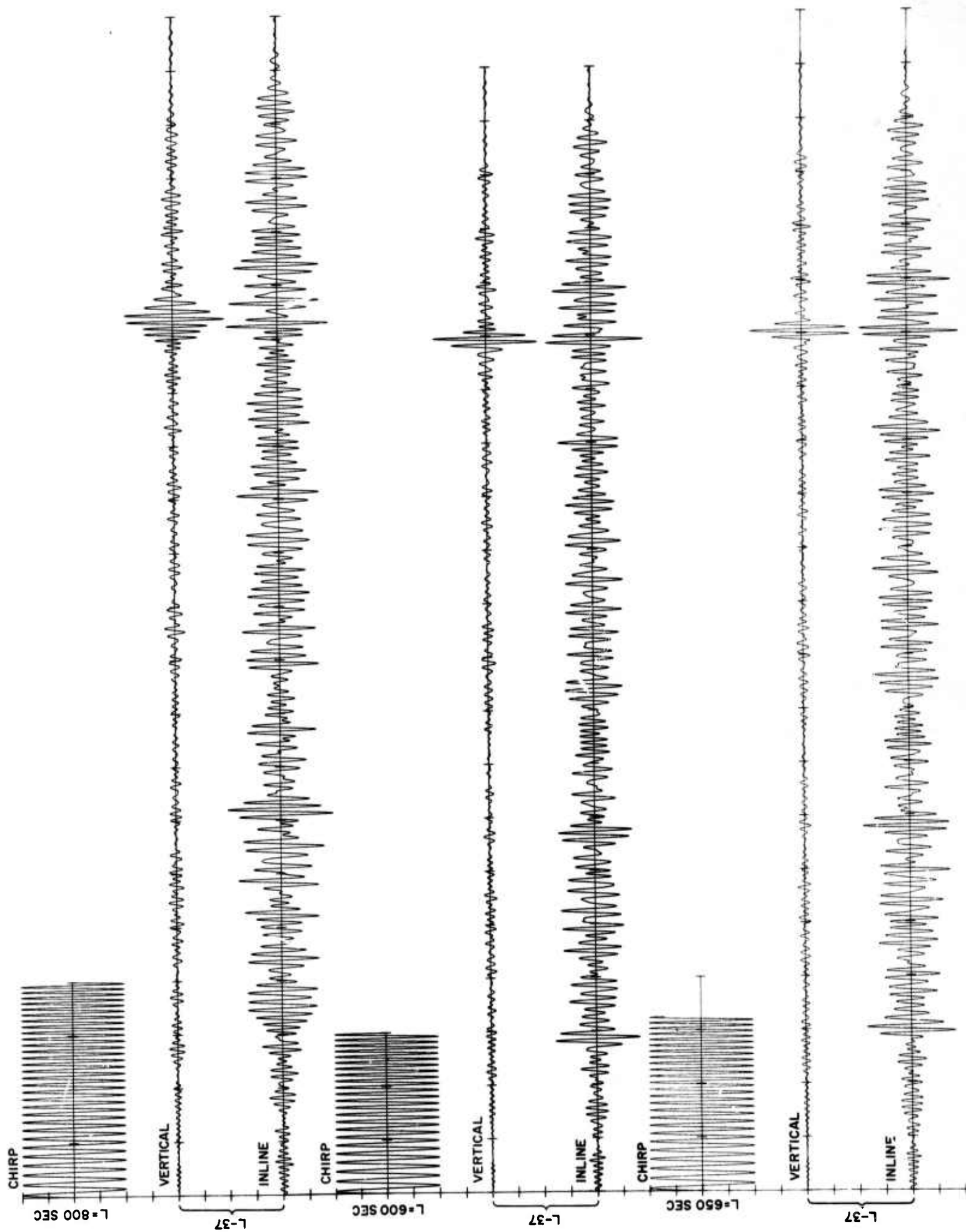


Figure 16. Plotted Results of Applying Chirp Filters of Three Durations to Vertical and Inline Traces of Event L-37



the low frequencies are shifted early, indicating that the chirp-filter frequency is changing too fast. Figure 16 shows the results for a 650-sec filter — the best match obtained. As expected, the S/N ratio improvement is somewhat less than that obtained from the ME filter.

In Figure 17 are the 15 individual seismometer channels for event L-37 and the matched-filter results using the 650-sec chirp filter. Channels F3, D4, D1, and F1 show poor S/N ratios on the matched-filter outputs; this results primarily from the isolated large noise excursions seen on the input traces. The noise pulses are probably nonseismic. These outputs indicate four channels which, if used, could seriously degrade the beamsteered output and subsequent matched-filtering results.

For the remaining 11 channels, the peak of the matched-filter output is timed for use in stacking the channels. This technique yields an optimum beamsteered output as opposed to one using theoretical traveltimes, where the energy is assumed to propagate along the great circle path from epicenter to LASA. The 11 channels are restacked using the measured delays and filtered using the 650-sec chirp. The output is shown in Figure 17. The S/N ratio improves slightly over that for the chirp result shown in Figure 16; the improvement results primarily from omitting the four noisy channels from the beamsteer. The measured delays are close to the theoretical delays for this event, the maximum difference being three samples (seconds). The 11-channel beamsteer shows a 4.5-db S/N ratio improvement, and the matched-filter beamsteer shows an 18.5-db S/N ratio improvement over the raw time traces.

The frequency response of the 650-point chirp filter is shown in Figure 18. The bandpass characteristic results from specification of the initial and final frequencies in the filter calculation. This raised the question of how much S/N ratio improvement could be attributed to simple bandpass



filtering of the input traces. A zero-phase bandpass filter closely approximating the response of the chirp filter was designed and applied to the L-37 channels, yielding the results shown in Figure 18. The average S/N ratio improvement is 2 db over the raw time traces.

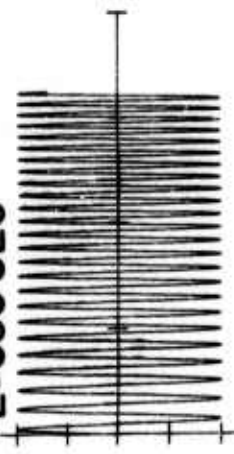
One additional question concerning matched filtering is how critical is the design of the matching filter. This may be answered by seeing how much distance can be allowed between the epicenter of a master event and the epicenter of an event to which it can be successfully applied. In geographical areas where matched-filtering results are poor, ^{*} this distance must be small (<200 km), but this need not be true in other areas.

Shown in Figure 19 are the beamsteered vertical and inline traces for earthquake L-62 ($m_b = 4.3$). The event is approximately 370 km farther from LASA and located southeast of L-37. The ME filter from L-37 is applied to event L-62, yielding the results shown in Figure 19. The S/N ratio improvement is about 6 db over the raw time traces.

* Texas Instruments Incorporated, 1970: Seismic Array Processing Techniques, Quarterly Report No. 2, Contract F33657-70-C-0100, AFTAC, 3 March.

CHIRP

L=650 SEC



CHANNEL F3



F3 MATCHED FILTERED



CHANNEL F4



F4 MATCHED FILTERED



CHANNEL C4



C4 MATCHED FILTERED



CHANNEL C1



A₁

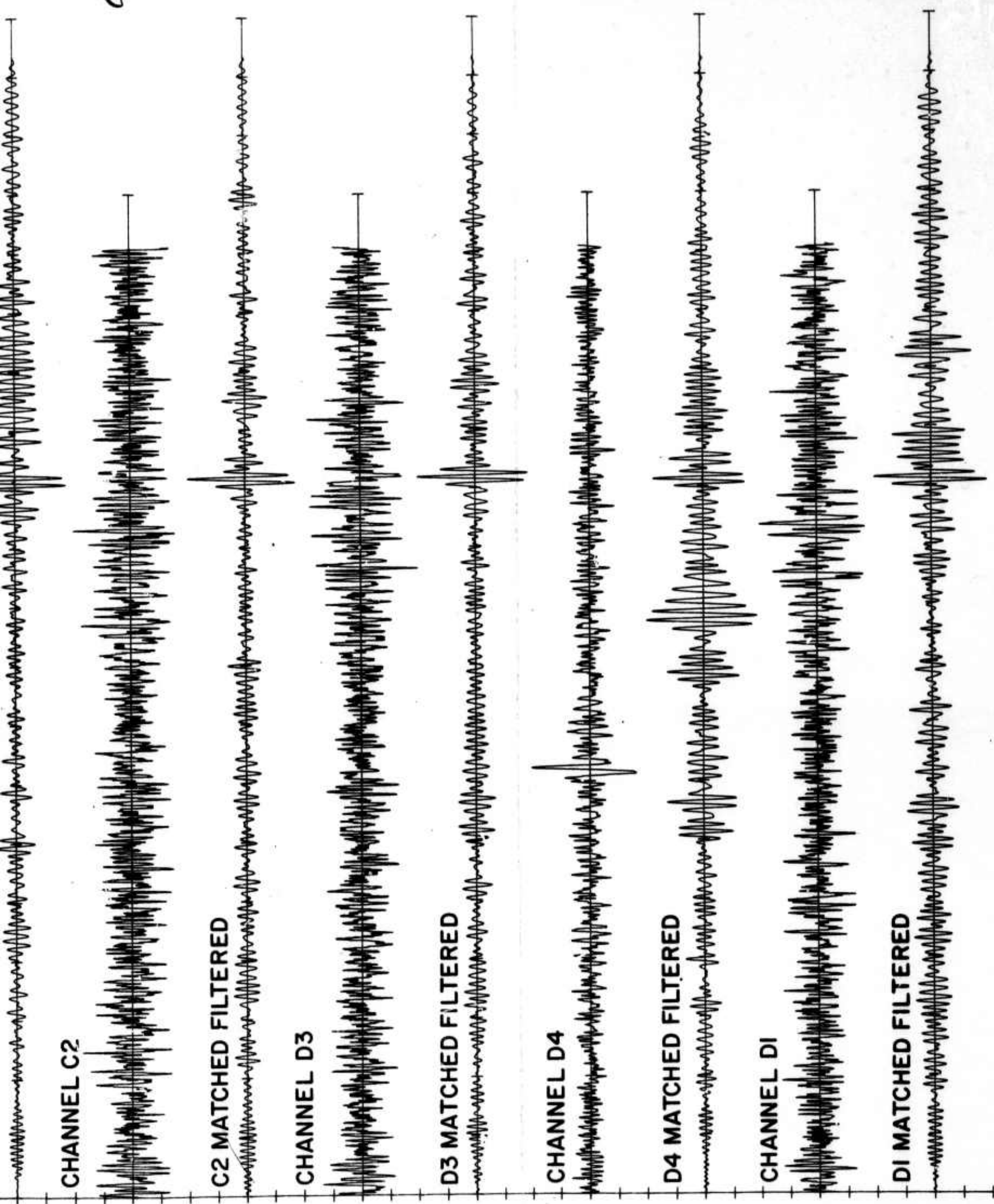
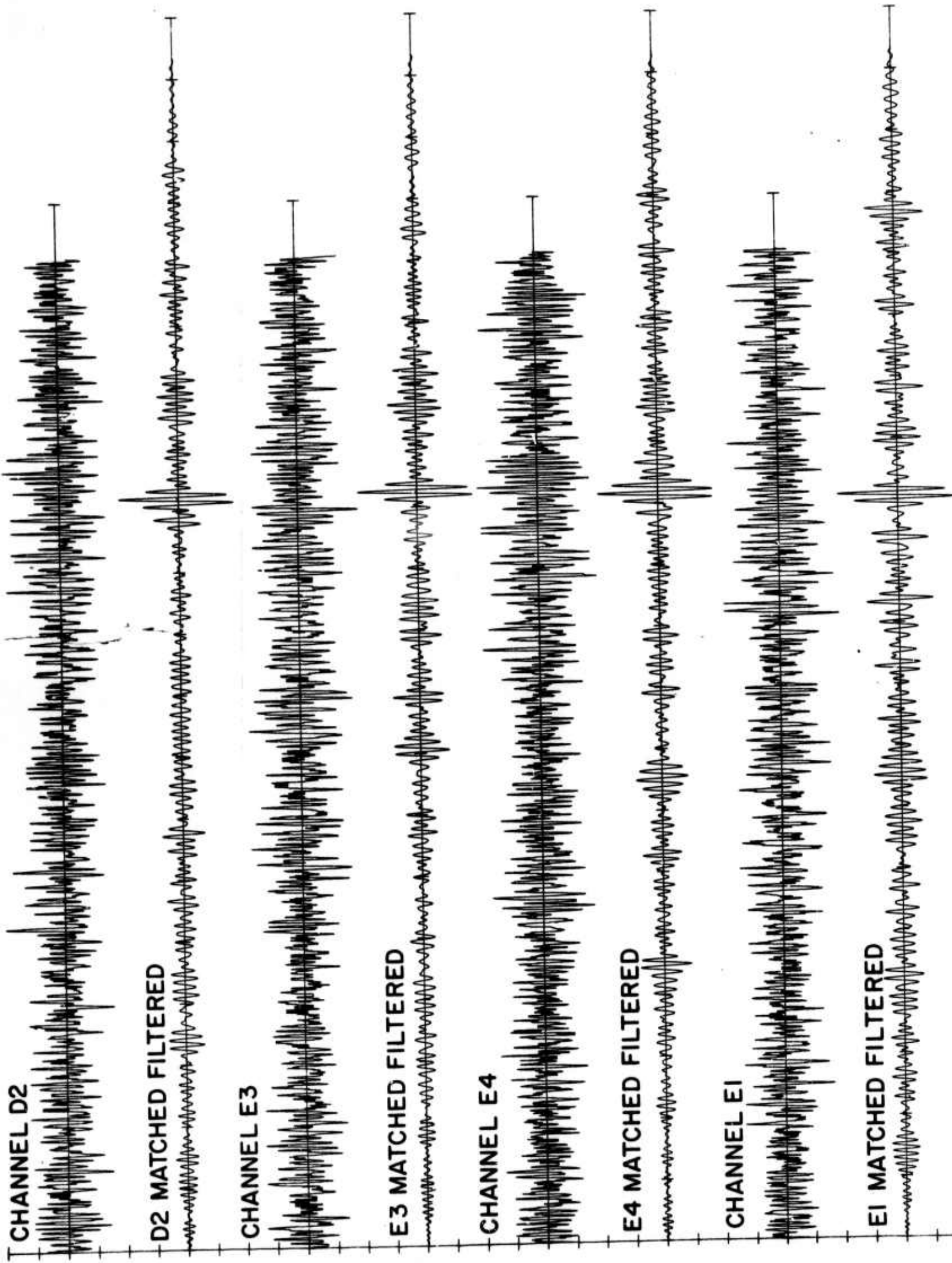


Figure 17. Plotted Results of Applying Chirp Filter of 650-Sec Duration to Individual Channels of Event L-37 (Page 1 of 2)

R

A.



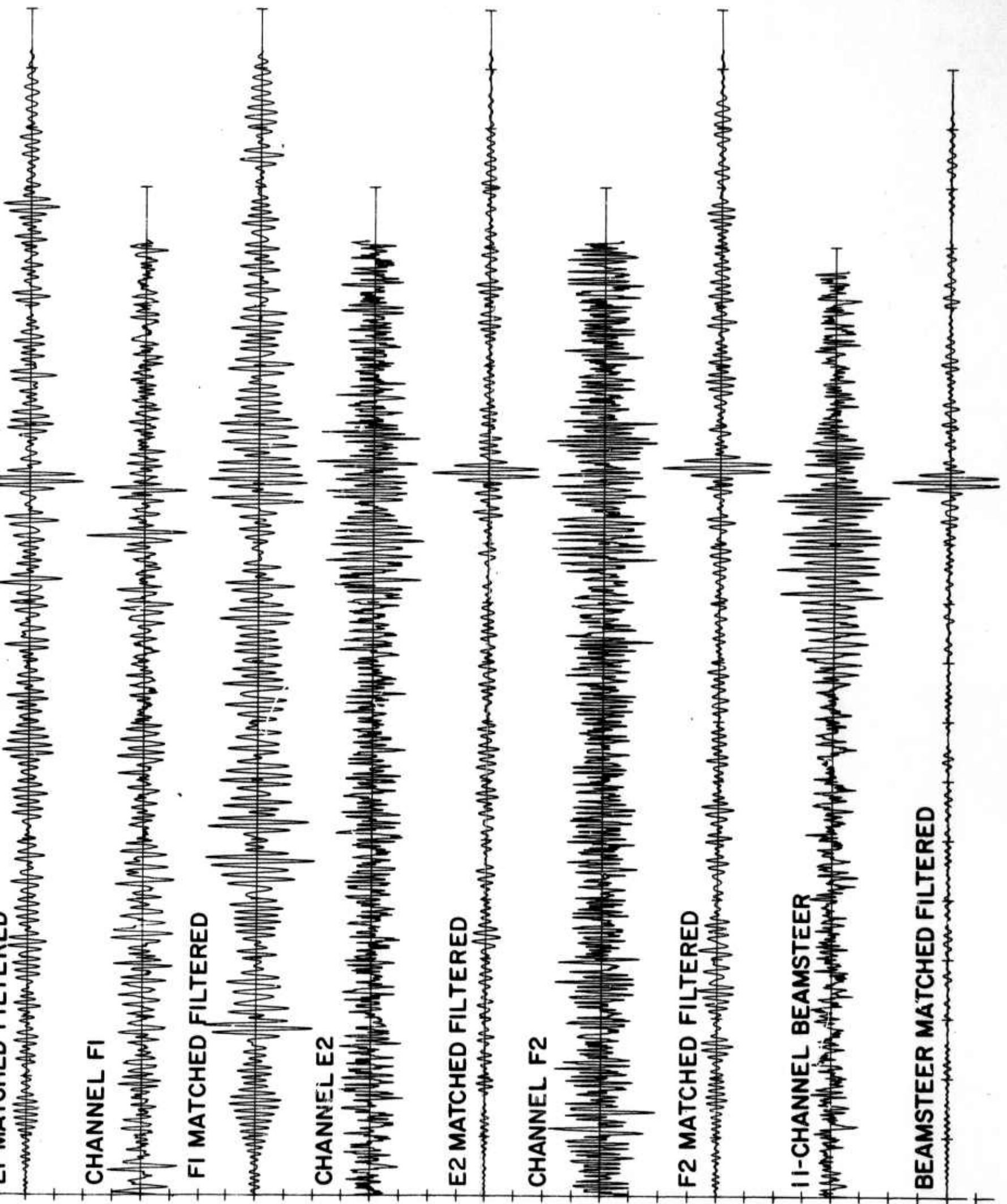
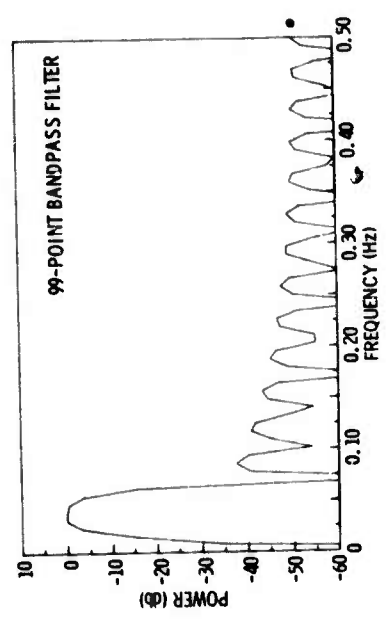
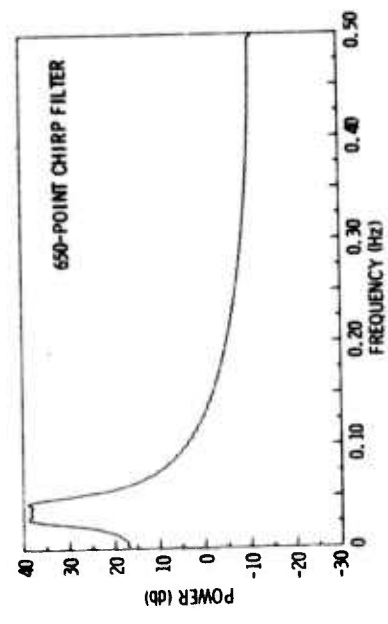


Figure 17. (Page 2 of 2)

A.



BANDPASS FILTER



CHANNEL F3

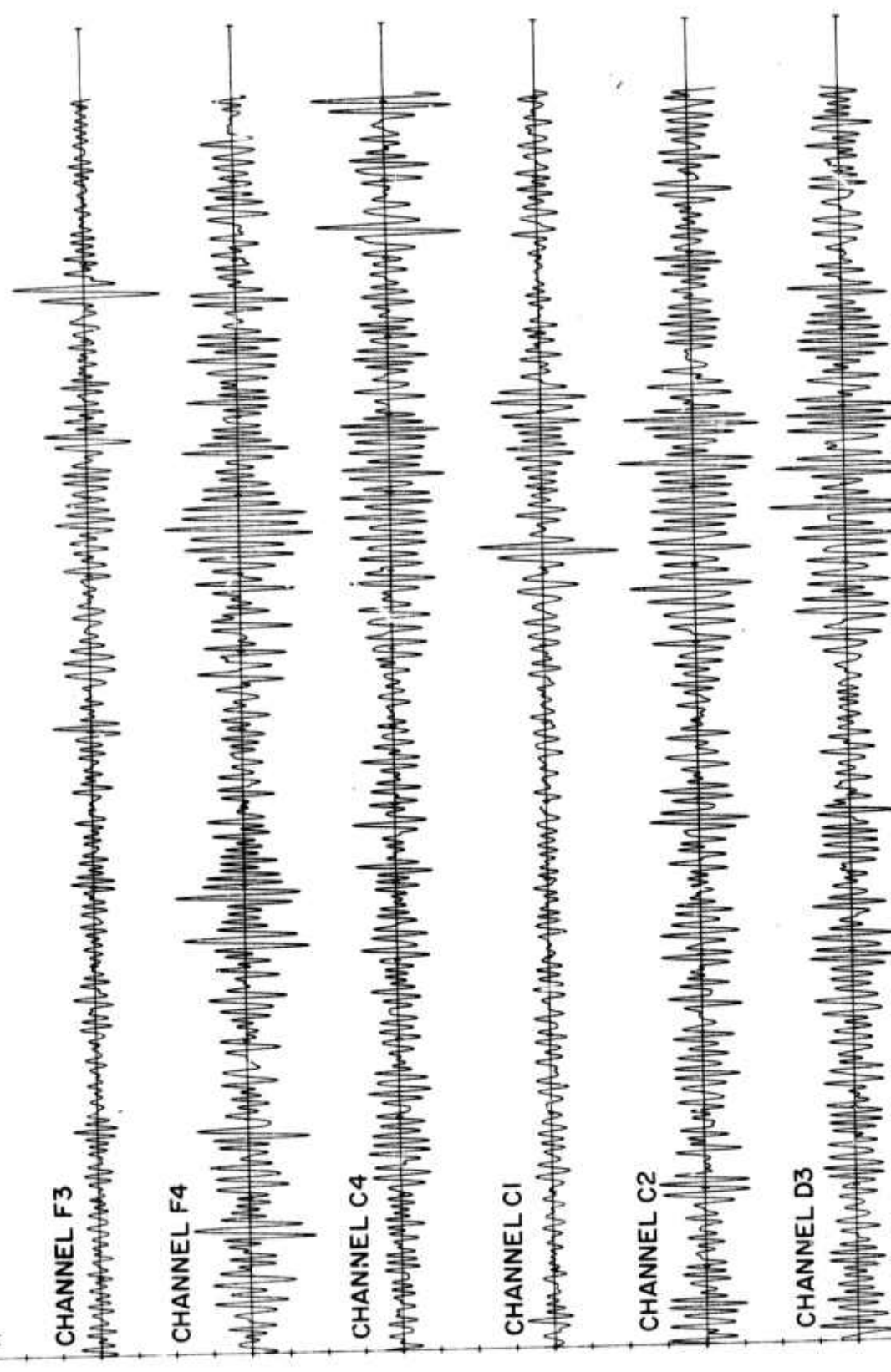
CHANNEL F4

CHANNEL C4

CHANNEL C1

CHANNEL C2

CHANNEL D3



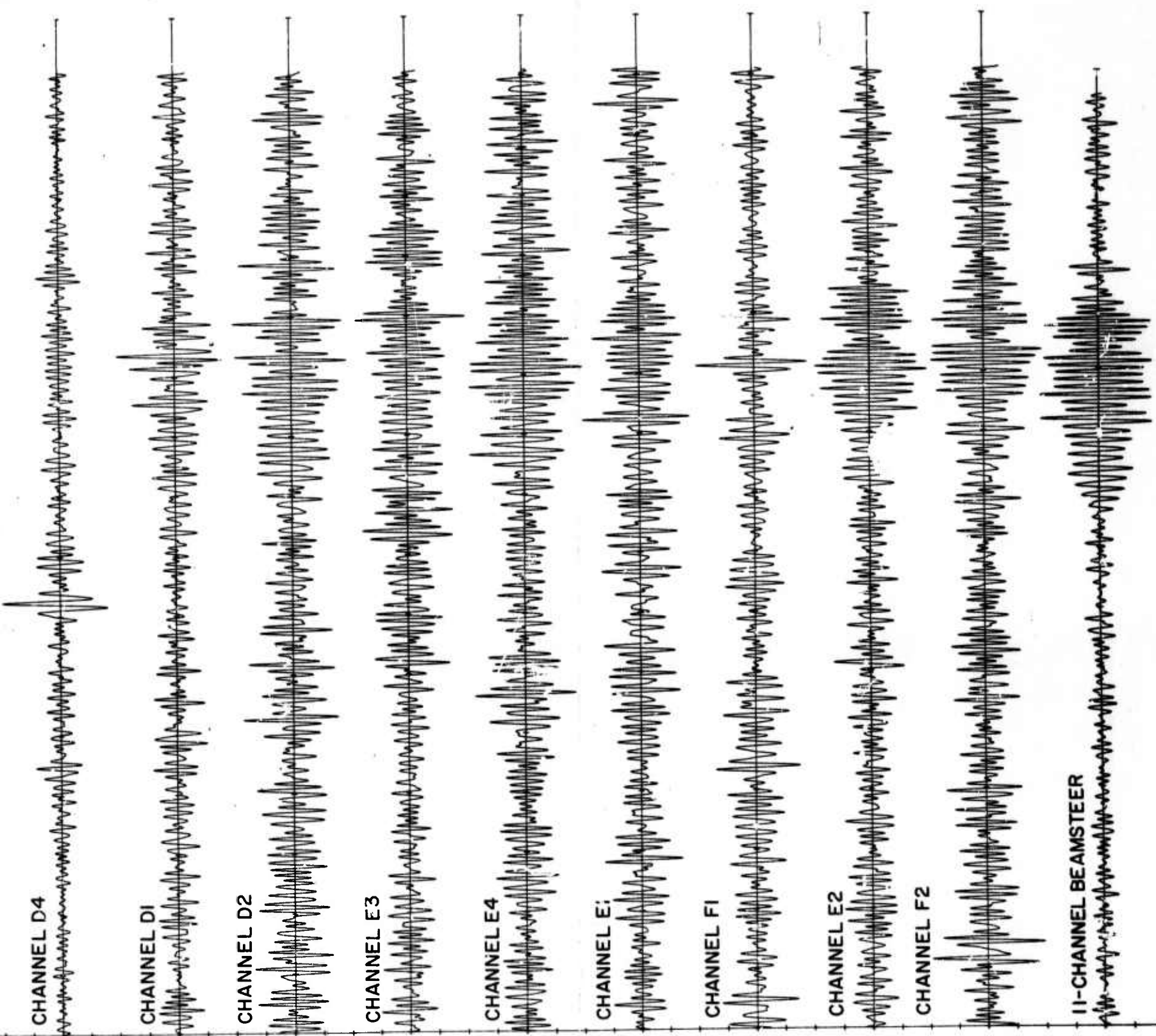
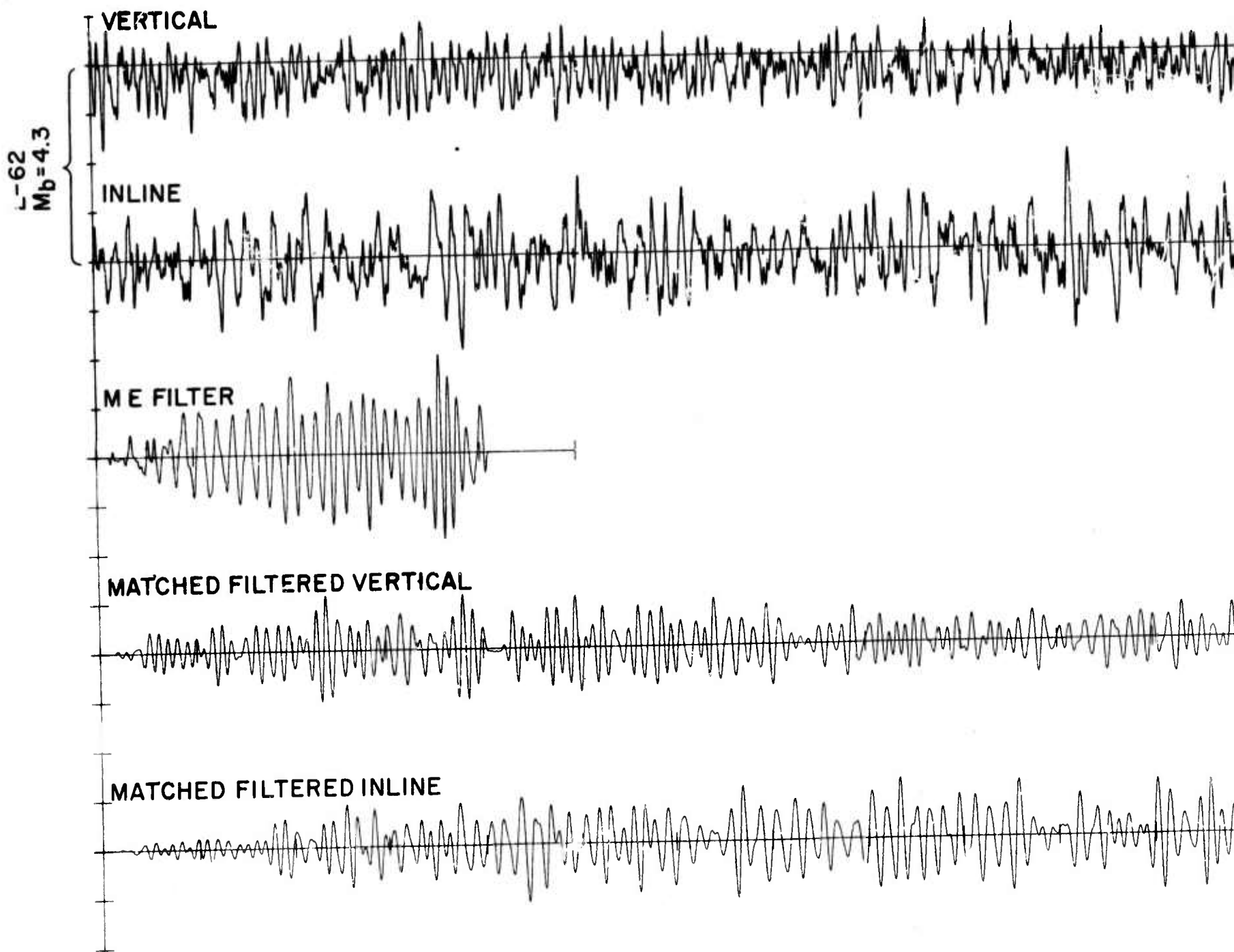
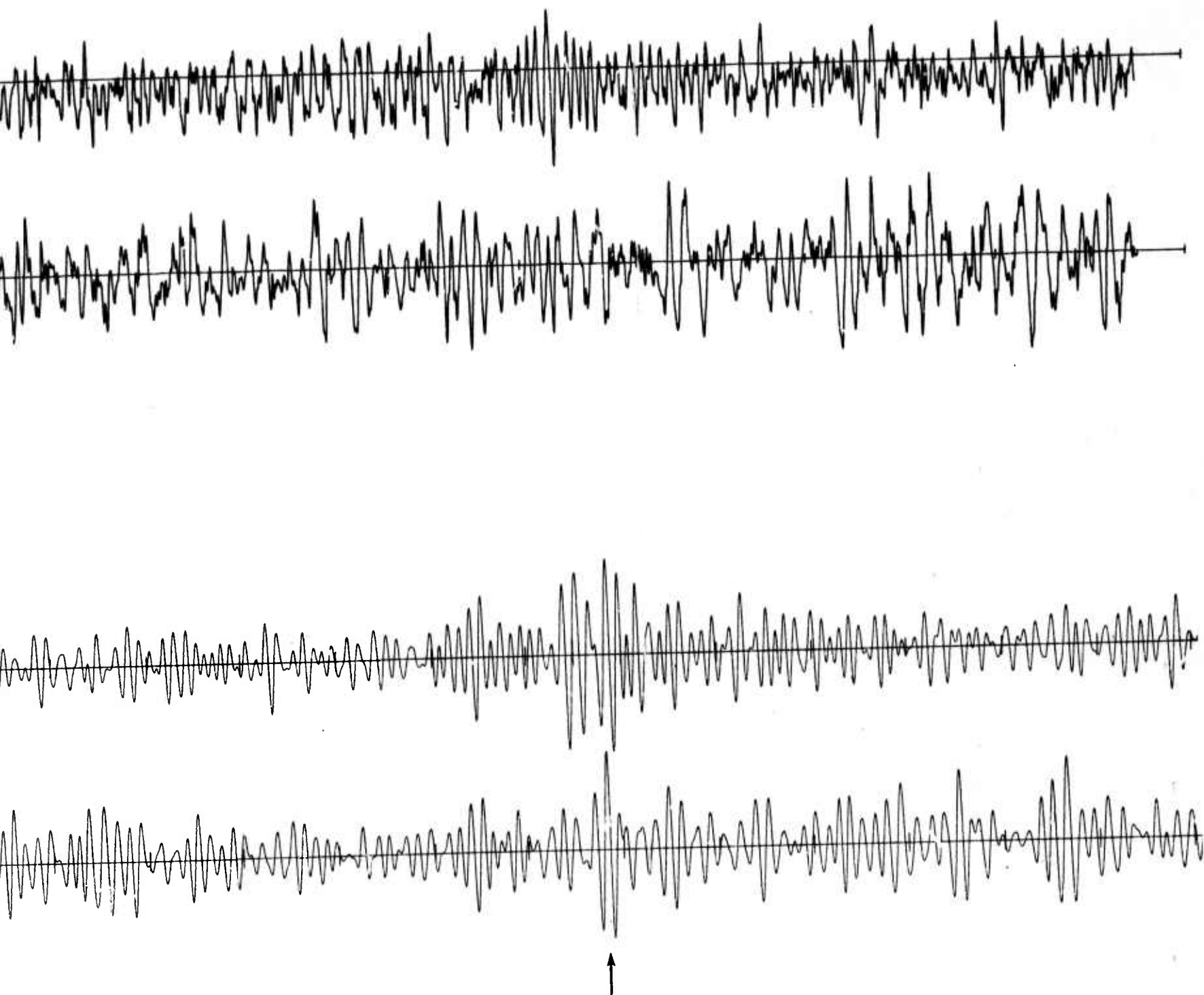


Figure 18. Frequency Response of 650-Sec Chirp Filter and Results of Applying Equivalent Zero-Phase Bandpass Filter to Individual Channels of Event L-37



A.



Q

Figure 19. Beamsteered Vertical and Inline Traces for Event L-62 and Results of Applying Master-Event Filter from Event L-37

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13. ABSTRACT			
<p>A new and larger learning ensemble was assembled to better represent the area under study and to better represent the two classes of events statistically. The effectiveness of various short-period statistics for discrimination was studied. Higher-order surface modes were sought in two long-period events by obtaining estimates of group velocity from maximum-entropy spectral peaks measured over short time gates of the seismogram. Definition of the fundamental Rayleigh mode was good, and possible higher-mode energy was indicated. Matched filtering was performed on a suite of long-period explosion recordings. Chirp filters worked almost as well as master events.</p>			

KEY WORDS

LINK A

LINK B

LINK C

ROLE

WT

NAME	ROLE
Mr. J. Edgar Hoover	Director
Mr. Clegg	Chief of Bureau
Mr. Glavin	Chief of Bureau
Mr. Ladd	Chief of Bureau
Mr. Nichols	Chief of Bureau
Mr. Rosen	Chief of Bureau
Mr. Tracy	Chief of Bureau
Mr. Carson	Chief of Bureau
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Matched Filtering